

The Manufacture of Minoan Metal Vessels: Theory and Practice

by

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Volume I: Text

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For Alex and Cara

Statement of Originality

The work presented in the thesis is, to the best of my knowledge and belief, original and my own work except as acknowledged in the text. The material has not been submitted, either in whole or in part, for a degree at the Australian National University or any other university.

A handwritten signature in black ink, reading "Christina Clarke.", is positioned above a horizontal line.

Christina Clarke

October 2012

Abstract

This study aims to establish the equipment and methods used to make hammered metal vessels in Crete during the Bronze Age. It combines archaeological research with metalsmithing practice. The most substantial studies to date have been largely typological. Some have examined the equipment and processes used, but usually without fully taking into account the metalsmithing techniques involved in vessel manufacture. An understanding of the equipment required and the manner in which it is used provides a new perspective on the Minoan craft and its practitioners.

The initial stages of the study involved investigating Minoan vessel types and characteristics, and studying excavation reports on Bronze Age metallurgical sites in Crete as well as publications on the metallurgy of Minoan Crete and other Bronze Age cultures. The second stage was the detailed examination of a number of Minoan vessels in collections in Crete and the UK. The final stage was to replicate tools and equipment found at Minoan metallurgical sites and to test their viability for making Minoan metal-vessel forms. The processes involved annealing, the application of different hammering methods, riveting and polishing techniques. These reconstructed processes led to the creation of two small bowls, a hydria made from separate sections and a one-handled basin.

The results of this research and the replication of equipment and techniques made it possible to reconstruct the processes used to make these vessels. Several other discoveries were made which have broader implications. Firstly, the reconstructive process revealed some of the physical aspects of the craft which would have affected the working practices of Minoan smiths and the roles of individuals within a workshop. Secondly, the study showed that simple tools found at many Minoan metallurgical sites are very effective for creating these vessels. Furthermore, the results suggest that metalsmithing may have occurred at more locations than are currently recognised as metallurgical sites. Lastly, it was discovered that both the forms and the often large sizes of Minoan vessels and, by extension, many Mycenaean vessels were determined by the types of tools that the smiths used. This has implications for how we might interpret these vessels within the broader context of the metal-vessel traditions of other contemporary cultures.

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Abbreviations

†	In Chapter Four, this symbol denotes an artefact which comes from a confirmed metallurgical context.
*	In Chapter Six and Appendix One, the asterisk denotes a Minoan metal vessel for which I have assigned a <i>BKMK</i> type number according to my observations. These vessels have not previously been classified within the <i>BKMK</i> typology.
<i>AGSW</i>	Davis, E. N. <i>The Vapheio Cups and Aegean Gold and Silver Ware</i> . London: Garland Publishing, 1977.
<i>AJA</i>	<i>American Journal of Archaeology</i>
<i>AM</i>	Branigan, K. <i>Aegean Metalwork of the Early and Middle Bronze Age</i> . Oxford: Clarendon Press, 1974.
<i>ANM</i>	Ayios Nikolaos Archaeological Museum
<i>Annuario</i>	<i>Annuario della Scuola archeologica di Atene e delle missioni italiane in Oriente</i>
<i>Antiquity</i>	<i>Antiquity. A Quarterly Review of Archaeology</i>
<i>ArchKorrBl</i>	<i>Archäologisches Korrespondenzblatt</i>
<i>AshM</i>	Ashmolean Museum
<i>BAR-IS</i>	British Archaeological Reports, International Series
<i>BCH</i>	<i>Bulletin de correspondance hellénique</i>
<i>BKMK</i>	<i>Die Bronzegefäße der kretisch-mykenischen Kultur</i>
<i>BLMC</i>	Hakulin, L. <i>Bronzeworking on Late Minoan Crete : A Diachronic Study</i> BAR-IS 1245. Oxford: Archaeopress, 2004.
<i>BM</i>	British Museum
<i>BSA</i>	<i>Annual of the British School at Athens</i>
<i>BSA Suppl.</i>	Supplementary Volume to the <i>Annual of the British School at Athens</i>
<i>CBAC</i>	Mangou, H., and P. V. Ioannou. "On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from Crete." <i>BSA</i> 93 (1997): 91-102.
<i>CBAUM</i>	Catling, H. W., and R. E. Jones. "Analyses of Copper and Bronze Artefacts from the Unexplored Mansion, Knossos." <i>Archaeometry</i> 19 (1977): 57-66.
<i>CBMW</i>	Catling, H. W. <i>Cypriot Bronzework in the Mycenaean World</i> . Oxford: Clarendon Press, 1964.
<i>CM</i>	Chania Archaeological Museum
<i>EJA</i>	<i>European Journal of Archaeology</i>
<i>EBA</i>	Early Bronze Age

ÉtCrét	Études Crétoises
HM	<i>Historical Metallurgy</i>
HM	Heraklion Archaeological Museum
JANES	<i>Journal of the Ancient Near East Society of Columbia University</i>
JFA	<i>Journal of Field Archaeology</i>
JMA	<i>Journal of Mediterranean Archaeology</i>
<i>Kommos I: Part 1</i>	Shaw, J. W., and M. C. Shaw, eds. <i>Kommos I: The Kommos Region and Houses of the Minoan Town. Part 1: The Kommos Region, Ecology, and Minoan Industries</i> . Princeton: Princeton University Press, 1995.
<i>Kommos I: Part 2</i>	Shaw, J. W., and M. C. Shaw, eds.. <i>Kommos I: The Kommos Region and Houses of the Minoan Town. Part 2, The Minoan Hilltop and Hillside Houses</i> . Princeton: Princeton University Press, 1996.
<i>Kommos V</i>	Shaw, J. W., and M. C. Shaw, eds. <i>Kommos V: The Monumental Minoan Buildings at Kommos</i> . Princeton: Princeton University Press, 2006.
LBA	Late Bronze Age
LC	Late Cypriot
LH	Late Helladic
MBA	Middle Bronze Age
MELETEMATA	Betancourt, P. P., and V. Karageorghis, eds. <i>MELETEMATA. Studies in Aegean Archaeology Presented to Malcolm H. Wiener as He Enters his 65th Year</i> . Aegaeum 20. Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1999.
Met	Metropolitan Museum of Art
MFGS	Soles, J. S., and Z. A. Stos-Gale. "The Metal Finds and their Geological Sources." In <i>Mochlos IC</i> , edited by J. S. Soles and C. Davaras, 45-59. Philadelphia: INSTAP Academic Press, 2004.
MMS	<i>Metropolitan Museum Studies</i>
<i>Mochlos IA</i>	Soles, J. S., and C. Davaras, eds. <i>Mochlos IA: Period III, Neopalatial Settlement on the Coast: The Artisans' Quarter and the Farmhouse at Chalinomouri</i> . Philadelphia: INSTAP Academic Press, 2003.
<i>Mochlos IC</i>	Soles, J. S., and C. Davaras, eds. <i>Mochlos IC: Period III. Neopalatial Settlement on the Coast, the Artisans' Quarter and the Farmhouse at Chalinomouri: The Small Finds</i> . Philadelphia: INSTAP Academic Press, 2004
MusPig	Museo Pigorini
NM	National Archaeological Museum of Athens

<i>OJA</i>	<i>Oxford Journal of Archaeology</i>
OMQM	Éluère, C. "Appendice III. Étude en laboratoire de quelques objets métalliques du Quartier Mu." In <i>Artisans minoens: Les Maisons-Ateliers du quartier Mu</i> , edited by J.-C. Poursat, 141-148. ÉtCrét 32. Athens: École Française d'Athènes, 1996.
Penn	University of Pennsylvania Museum of Archaeology and Anthropology
<i>POLITEIA</i>	Laffineur, L. and W. -D. Niemeier, (eds). <i>POLITEIA. Society and State in the Aegean Bronze Age: Proceedings of the 5th International Aegean Conference / 5e Rencontre égéenne internationale, University of Heidelberg, Archäologisches Institut, 10-13 April 1994</i> . Aegaeum 12. Liège: Université de Liège, 1995.
SIMA	Studies in Mediterranean Archaeology
ST4	Catling, H. W., and R. E. Jones. "Sellopoulo Tomb 4: Some Analyses." <i>BSA</i> 71 (1976): 21-23.
<i>TEXNH</i>	Laffineur, R., and P. P. Betancourt, eds. <i>TEXNH. Craftsmen, Craftswomen and Craftsmanship in the Aegean Bronze Age / Artisanat et artisans en Égée à l'âge du Bronze: Proceedings of the 6th International Aegean Conference / 6e Rencontre égéenne internationale, Philadelphia, Temple University, 18-21 April 1996</i> . 2 vols, Aegaeum 16. Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1997.
<i>TUAS</i>	<i>Temple University Aegean Symposium</i>

Vessel Hammering: The Process Frequently Overlooked

At some stage during the Early Bronze Age, smiths in Crete either learned or discovered how to hammer a piece of metal into a thin-walled vessel. During these early stages, such vessels were probably made from precious metals, which were soft and easy to work, but as pyrotechnology advanced and the characteristics of alloys came to be understood during the Middle and Late Bronze Ages, vessels were also made from arsenic bronzes and, later, tin bronzes. Today, we have some understanding of the value of these vessels in social and symbolic terms, and of the methods used to make them. What has not been understood is how they were actually made. A handful of artefacts have been identified which have the potential to be used as tools to make vessels, but the question as to how these tools were used is not asked.

The technique of hammering metal vessels is frequently overlooked in studies of prehistoric metallurgy, the focus usually being in favour of large-scale technology such as smelting or more glamorous techniques such as jewellery-making. In some cases, vessel-making seems to be regarded as one of the lesser skills of the metalsmith. In referring to the precious metal vessels of the Bronze Age Aegean civilisations, Branigan states that “they in fact demanded relatively few skills of their manufacturers” and that “the ability to hammer and to solder was all that was needed to produce these vessels.”¹ Often, in discussions of the manufacture of vessels in antiquity, the topic of hammering or beating sheet is briefly mentioned and then passed by with no further explanation or the use of sinking and raising is mentioned without much understanding of the techniques.² In truth, the technique of hammering vessels is an extremely advanced technique which requires years of training and practice for an individual to master and generations to develop in complexity.

In order to create a vessel, the smith must have an intimate understanding of the movement of metal and the experience to recognise which tools are appropriate for creating desired profiles and exactly where and how these tools must be applied. It is also a craft that requires patience and forethought, because making a vessel is a long-term project. Creating a complex vessel can take months of effort. If a mistake is made

¹ K. Branigan, *Aegean Metalwork of the Early and Middle Bronze Age* (Oxford: Clarendon Press, 1974), 92.

² e.g. E. N. Davis, *The Vapheio Cups and Aegean Gold and Silver Ware* (London: Garland Publishing, 1977), 350.

late in the process, the entire vessel can be ruined and the time taken is lost. Small errors at early stages can cause irreversible problems which are not necessarily apparent until the work is almost complete. Far from a basic skill, vessel-making is one of the most complex of the techniques used by smiths in prehistory, as it remains today.

Aims of the Study

The primary aim of this study is to reconstruct how metal vessels were made in Crete during the Bronze Age. This entails ascertaining the techniques used to make them and the equipment which was required. A secondary aim is to describe how metal vessels were made in a manner which is understandable to scholars who do not have metalsmithing experience. Most reference materials on modern metalworking are manuals for metalsmiths, and they are frequently written in a way that is difficult to understand unless the reader is already familiar with the practice. It is hoped that a thorough technical explanation of these methods will demystify them and prevent misunderstandings about vessel-making from marring future research, as has happened in the past. In addition, I hope that the technical descriptions provided here can be used by scholars as reference material for describing the construction of hammered metal-vessels in future studies.

A distinctive element in this study is the practical reconstruction of Minoan metalsmithing techniques with replicated equipment. This approach should provide a twofold contribution because not only will it elucidate the technical aspects of the craft, but it may provide new information about Minoan smiths' work practices, leading to a fuller understanding of Minoan culture.

Context of the Study

Minoan Vessels

In the first place, I will discuss the major publications concerning Minoan metal vessels. Further details of these studies are evaluated in later chapters where they are most relevant.

Most studies of Minoan metal vessels have been catalogues, two of which include typologies. These publications are indispensable reference works for a study such as this one. Catling's 1964 *Cypriot Bronzework in the Mycenaean World* was the first

publication to collect together known bronze vessels from Crete and mainland Greece and to categorise the vessels by type.³ For the first time, it was possible to compare vessels from around the Aegean and to attempt to establish patterns. Catling concludes, however, that there are insufficient surviving vessels to allow scholars to arrive at firm conclusions.⁴ Popham, Catling and Catling added further to this catalogue of vessels in 1974 with the study “Sellopoulo Tombs 3 and 4, Two Late Minoan Graves Near Knossos.”⁵

Also in 1974, Branigan’s *Aegean Metalwork of the Early and Middle Bronze Age* listed the bronze and precious-metal vessels found throughout the Aegean in the earlier stages of the Bronze Age.⁶ Extant metal-vessel finds from Crete are meagre during these periods, so although this catalogue is invaluable for the study of other metal items and for studies of vessels from the eastern Aegean (western Anatolia), it has little relevance for the current study.

In 1977, Davis published her comprehensive work on Minoan and Mycenaean precious metal vessels, *The Vapheio Cups and Aegean Gold and Silver Ware*.⁷ Davis’s main concern was to determine the stylistic and technical differences between the metalworking methods used by Minoan and Mycenaean smiths to make precious-metal vessels. The illustrated catalogue of vessels in her study includes all of the precious-metal vessels known at the time, and today remains the primary reference for their study. Unfortunately, Davis did not develop a typology for the vessels, and there is none for precious-metal vessels to this day.

Matthäus’s 1980 publication *Die Bronzegefäße der kretisch-mykenischen Kultur* is both a comprehensive catalogue of every Mycenaean and Minoan bronze vessel known at that date and a detailed typology.⁸ It superseded Catling’s catalogue and typology and is now the primary reference for Minoan and Mycenaean bronze vessels. Without a doubt, this has been the greatest contribution to the field so far. It is unfortunate that the typology in *BKMK* covers only bronze vessels. A small number of precious-metal vessels are referred to when they match a bronze type, but the vessel types which do not exist in bronze are not covered at all.

³ H. W. Catling, *Cypriot Bronzework in the Mycenaean World* (Oxford: Clarendon Press, 1964).

⁴ *Ibid.*, 187.

⁵ M. R. Popham, E. A. Catling, and H. W. Catling, “Sellopoulo Tombs 3 and 4, Two Late Minoan Graves Near Knossos,” *BSA* 69 (1974): 225-254.

⁶ Branigan, *AM*.

⁷ Davis, *AGSW*.

⁸ H. Matthäus, *Die Bronzegefäße der kretisch-mykenischen Kultur*, *Prähistorische Bronzefunde*. Abteilung II; Bd. I (München: C.H. Beck, 1980).

The most recent catalogue of bronze vessels in Minoan Crete is in Hakulin's 2004 *Bronzeworking on Late Minoan Crete: A Diachronic Study*.⁹ This is an excellent reference for all known evidence of metallurgy in Late Bronze Age Crete, including every known bronze or copper item, crucible and mould, and every substantial metallurgical site. For bronze vessels, it builds on Matthäus's work by including bronze vessels which have been found since the publication of *BKMK*. It also includes all of the chemical analyses of bronze items then published. It is unfortunate that it covers only the Late Bronze Age, since similar data from earlier periods would be extremely useful.

Another type of study of Minoan vessels involves analyses of their metals to determine their compositions. Analyses of vessels and vessel parts have been published and discussed by several scholars. All of these are useful, but to varying extents. A paper by Catling and Jones published in 1976 identifies the specific vessels which had been analysed,¹⁰ and works by Mangou and Ioannou, Éluère, and Soles and Stos identify some vessels but not others.¹¹ Another paper by Catling and Jones published in 1977 identifies what parts of a vessel the samples were taken from – body, rim or handle – and describes the vessel shapes of others. More specific details would be helpful.¹² It is likely that some analyses are of fragments, and the vessel itself is unidentifiable. A paper by Evely and Stos provides summaries of their findings, but does not provide the data or identify the specific vessels analysed.¹³ It would be useful to combine the data from their study with those of the others studies mentioned to gain a broader picture of the use of alloys in vessels. It is regrettable that some analyses are published without describing the vessels from which they are taken, because it is possible that particular alloys were used to make vessels of a particular shape. This might have further implications for the technical and social aspects of Minoan metal vessels. Certain forms may have required particular alloys to enable their manufacture,

⁹ L. Hakulin, *Bronzeworking on Late Minoan Crete: A Diachronic Study* BAR-IS 1245 (Oxford: Archaeopress, 2004).

¹⁰ H. W. Catling and R. E. Jones, "Sellopoulo Tomb 4: Some Analyses," *BSA* 71 (1976).

¹¹ H. Mangou and P. V. Ioannou, "On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from Crete," *BSA* 93 (1997); C. Éluère, "Appendice III. Étude en laboratoire de quelques objets métalliques du Quartier Mu," in *Artisans minoens: Les Maisons-Ateliers du quartier Mu*, ed. Jean-Claude Poursat, *ÉtCrét* 32 (Athens: École Française d'Athènes, 1996); J. S. Soles and Z. A. Stos-Gale, "The Metal Finds and their Geological Sources," in *Mochlos IC*, ed. Jeffrey S. Soles and Costis Davaras (Philadelphia: INSTAP Academic Press, 2004).

¹² H. W. Catling and R. E. Jones, "Analyses of Copper and Bronze Artefacts from the Unexplored Mansion, Knossos," *Archaeometry* 19 (1977).

¹³ D. Evely and Z. A. Stos, "Aspects of Late Minoan Metallurgy at Knossos," in *Knossos: Palace, City, State*, ed. Gerald Cadogan, Eleni Hatzaki, and Andonis Vasilakis (London: British School at Athens, 2004).

for example, or certain vessel types may have been made from specific alloys for symbolic or ritual purposes.

Another type of chemical analysis attempts to identify the origins of the ores from which the metal was made using lead isotope analyses. These have implications for trade systems within the Aegean. This field has been pioneered and largely dominated by the work of Gale and Stos over the last few decades.¹⁴ There has been some opposition to these studies, especially because the combining of ores from different sources and the recycling of metals can confuse the data. There are also methodological issues.¹⁵ The only study which I am aware of that analyses Minoan vessels is that of Evely and Stos mentioned above.¹⁶ However, the provenances of the ores are not discussed with reference to individual items, but rather to sample sets which include vessels, tools and weapons, so there is not much information to draw from this in relation to vessels. In the present study, the subject of the provenance of ores is not broached since there is insufficient data specific to vessels to draw conclusions as to the relevance of the sources of the ores.

Leaving aside the question of the sources and composition of the metals, several of the above-mentioned catalogues attempt to describe how vessels were constructed. They tend, however, to be more descriptive than technical. For example, a vessel may be described as being made from two pieces of hammered sheet which are riveted together at the seam and with a cast handle riveted to the body. This type of description is common in Catling's *CBMW* and "Sellopoulo Tombs 3 and 4" and in Davis's *AGSW* and Matthäus's *BKMK*. We are left wondering, however, how the vessel was actually made: how the metal was transformed into this form, what tools were used and how.

¹⁴ e.g. N. H. Gale et al., "Copper Sources and Copper Metallurgy in the Aegean Bronze Age," in *Furnaces and Smelting Technology in Antiquity* ed. P. T. Craddock and M. J. Hughes (London: British Museum Press, 1985); N. H. Gale, "Copper Oxhide Ingots: Their Origin and their Place in the Bronze Age Aegean," in *Bronze Age Trade in the Mediterranean. Papers Presented at the Conference held at Rewley House, Oxford, in December 1989*, ed. N. H. Gale, *Studies in Mediterranean Archaeology* 90 (Jonsered: Paul Åströms Förlag, 1991); Z. A. Stos-Gale, "The Role of Kythnos and Other Cycladic Islands in the Origins of Early Minoan Metallurgy," in *Kea-Kythnos: History and Archaeology. Proceedings of an International Symposium, Kea-Kythnos, 22-25 June 1994*, ed. L. G. Mendoni and A. Mazarakis Ainan (Athens: 1998); Z. A. Stos-Gale, "Minoan Foreign Relations and Copper Metallurgy in Protopalatial and Neopalatial Crete," in *The Social Context of Technological Change: Egypt and the Near East, 1950-1550 BC*, ed. Andrew J. Shortland (Oxford: Oxbow Books, 2001); N. H. Gale and Z. A. Stos-Gale, "Cross-Cultural Minoan Networks and the Development of Metallurgy in Bronze Age Crete," in *Metals and Mines: Studies in Archaeometallurgy*, ed. Susan La Niece, Duncan Hook, and Paul Craddock (London: Archetype Publications, 2007).

¹⁵ e.g. P. Budd, "Oxhide Ingots, Recycling and the Mediterranean Metals Trade," *JMA* 8 (1995); A. B. Knapp, "Archaeology, Science-Based Archaeology and the Mediterranean Bronze Age Metals Trade," *EJA* 3 (2000); cf. N. H. Gale, "Archaeology, Science-Based Archaeology and the Mediterranean Bronze Age Metals Trade: A Contribution to the Debate," *EJA* 4 (2001).

¹⁶ Evely and Stos, "Aspects of Late Minoan Metallurgy at Knossos."

When attempts are made to describe the actual processes used, they are usually set out in general terms. Raising and sinking are sometimes specified without further detail, and it is rare for the tools to be referred to in these descriptions.¹⁷ Quite often, the functions of some metalsmithing techniques are misunderstood.¹⁸

The most detailed study of how metal vessels were made is Evely's *Minoan Crafts: Tools and Techniques: An Introduction*, published in two volumes in 1993 and 2000.¹⁹ This is the most substantial work on the various crafts practised by the Minoans, with descriptions of the many different processes required within a craft to make an object. In addition, these processes are described with reference to many specific objects and to the relevant tools and sites. Specifically, Evely provides the most detailed information so far published on some of the processes which were required to make Minoan metal vessels.²⁰ What remains to be explained is how the equipment was applied to the task. This study aims to build on Evely's work by filling this gap.

I have found only two works which have attempted to establish how tools were used to make vessels in prehistory, and both involved practical reconstructions, but based on flawed premises. Knauth, in his 1974 publication *The Metalsmiths*, reports and illustrates an experiment by silversmith Kurt Matzdorf using the shank bone of a sheep as a hammer to create a small silver bowl.²¹ The experiment is very interesting, but not scholarly. The book is intended only as a general introduction to ancient metallurgy. The experiment does not refer to any specific culture, period or artefacts. In addition, it is clear from the photographs that modern tools have been used for some stages of making the bowl, though these are not acknowledged.²² More focused is Johnson's recreation of New Kingdom Egyptian metalworking methods on the basis of depictions of metalworkers in the Theban tomb of Rekhmire.²³ Using some of the technology illustrated in the tomb, Johnson successfully creates a small hemispherical silver bowl. It is clear that Johnson did not intend with his experiment to provide a scholarly study involving archaeological reconstruction, but rather to demonstrate that the equipment depicted in the Rekhmire tomb would have worked for vessel manufacture. As

¹⁷ e.g. Davis, *AGSW*, 350.

¹⁸ For example, Davis says that sinking is better suited for creating round-bottomed bowls, which is not entirely true. *Ibid.*, 350.

¹⁹ R. D. G. Evely, *Minoan Crafts: Tools and Techniques: An Introduction*, vol. 1, SIMA 92:1 (Göteborg: Paul Åströms Förlag, 1993); R. D. G. Evely, *Minoan Crafts: Tools and Techniques: An Introduction*, vol. 2, SIMA 92:2 (Jonsö: Paul Åströms Förlag, 2000).

²⁰ Evely, *Minoan Crafts* 1, 97-102; Evely, *Minoan Crafts* 2, 381-387.

²¹ P. Knauth, *The Metalsmiths* (New York: Time-Life Books, 1974), 74-75.

²² The rim of the bowl has been caulked, which is not possible with a bone hammer, and the surface has been planished, clearly with a steel hammer.

²³ G. K. Johnson, "An Experiment in Ancient Egyptian Silver Vessel Manufacture," *JANES* 8 (1976).

interesting and useful as this work is, however, there is much to be desired in both detail and accuracy. The bowl is of a very basic design, and so does not test the full potential of the tools for making complex Egyptian vessels.²⁴ The choice of the hammer used is not based on any actual artefacts. There are also some assumptions made without justification. For example, the vessel is made from manufactured silver sheet, which is common today, but there is no attempt to prove that Egyptian vessels were in fact made from pre-formed sheet.

This brief survey reveals that there is a gap in our knowledge of vessel production between the metalsmithing equipment available and the achievement of the end product. The problem with leaving the question unanswered is that we are making assumptions without any basis about how some technology was used. As will become apparent later in this study, much of our interpretation of how Minoan smiths made vessels is based on a small and disparate number of bronze tools. It is natural that we might conclude that bronze tools were used for the process because a modern observer would note that modern metalsmiths use metal tools. However, I do not believe that we can simply assume that this has always been the case, and we should certainly not assume that we have answered the question by superimposing modern technology onto ancient.

Experimental Archaeology

Replication of and experimental reconstructions with ancient technologies is a common practice in modern archaeological studies and particularly archaeometallurgy. It is often used to interpret mining, smelting and casting methods and technologies.²⁵ In Minoan and Aegean archaeology, recent technological reconstructions have included replication of copper smelting furnaces,²⁶ Late Minoan pottery wheels,²⁷ and painted plaster.²⁸

²⁴ Essentially, the bowl's manufacture required only a small amount of sinking and optional raising, but it is clear that many Egyptian vessels were formed with extensive raising.

²⁵ e.g. Merkel, "Experimental Reconstruction of Bronze Age Copper Smelting based on Archaeological Evidence from Timna," in *The Ancient Metallurgy of Copper: Archaeology, Experiment, Theory*, ed. Beno Rothenberg (London: Institute for Archaeometallurgy Studies, 1990); G. Juleff, "An Ancient Wind-Powered Iron Smelting Technology in Sri Lanka," *Nature* 379, no. 6560 (1996); P. T. Craddock, I. F. Freestone, and C. D. Dawe, "Casting Metals in Limestone Moulds," *HM* 31 (1997); S. Van Lokeren, "Experimental Reconstruction of the Casting of Copper 'Oxhide' Ingots," *Antiquity* 74, no. 284 (2000); S. Timberlake, "The Use of Experimental Archaeology/Archaeometallurgy for the Understanding and Reconstruction of Early Bronze Age Mining and Smelting Technologies," in *Metals and Mines: Studies in Archaeometallurgy*, ed. Susan La Niece (London: Archetype Press, 2007).

²⁶ M. Catapotis and Y. Bassiakos, "Copper Smelting at the Early Minoan site of Chysokamino on Crete," in *Metallurgy in the Early Bronze Age Aegean*, ed. P. M. Day and Roger C. P. Doonan, Sheffield Studies in Aegean Archaeology (Oxford: Oxbow Books, 2007).

²⁷ J. E. Morrison and D. P. Park, "Throwing Small Vessels in the LM IB Potter's Pit," *Kentro* 10, no. Winter 2007-2008 (2007); D. Evelyn, "Materials and Industries," in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2010), 392.

Several scholars have proposed methodologies for carrying out experimental reconstruction in a way which provides reliable results. Coles created one of the earliest sets of such guidelines.²⁹ He suggests, amongst other things, that an experiment should be accurate to its ancient equivalent in its choice of materials and methods, that it should incorporate repetition and improvisation, and that it should be observed and assessed fairly and reported honestly. Essentially, Coles advocates an empirical approach to experimental archaeology.

In more recent discussion, the need for experiments to be empirical in nature has been elaborated. Guidelines developed by Kelterborn suggest that the procedure should follow the tenets of scientific experimentation by being clearly goal-oriented, measurable, repeatable, professionally planned and “executed with expert manual skill.”³⁰ Mathieu elaborates further on this, suggesting that experimental archaeology, like scientific experimentation, must be carried out in way in which the variables are controlled, and that experimentation should be concerned with the generation and testing of hypotheses.³¹

The problem with trying to reduce variables in archaeological experimentation of craft practices is that there are such a large number of unknown variables. Even within a single culture and period, each practitioner’s technique varies according to skill, strength, training, tradition, resources and personal preference. The most complex of these variables are those relating to tradition and culture; we cannot anticipate all of these factors in prehistoric craft practice. This makes it very difficult to limit all variables, because in some cases we are not even aware of what the variables are.

Jeffrey states that we must recognise the difference between experimental archaeology and experiential archaeology which, he says, are frequently confused.³² He states that experiential archaeology is “concerned with realistically performing tasks in a manner in which they were performed in the past” which is “very valuable in

²⁸ A. Brysbaert, “Does DIY Work? Experimentation and the Archaeology of Technology in an Aegean Bronze Age Context,” in *Symposium on Mediterranean Archaeology: Proceedings of the Sixth Annual Meeting of Postgraduate Researchers, University of Glasgow, Department of Anthropology, 15-17 February, 2002* ed. Ann Brysbaert, BAR-IS 1142 (Oxford: Archaeopress, 2003); A. Brysbaert, *The Power of Technology in the Bronze Age Eastern Mediterranean: The Case of the Painted Plaster*, Monographs in Mediterranean Archaeology 12 (London/Oakville: Equinox, 2008).

²⁹ J. Coles, *Archaeology by Experiment* (London: Hutchinson University Library, 1973), 15-18.

³⁰ P. Kelterborn, “Principles of Experimental Archaeology,” *Bulletin of Experimental Archaeology* 8 (1987).

³¹ J. Mathieu, “Introduction,” in *Experimental Archaeology: Replicating Past Objects, Behaviors, and Processes*, ed. James Mathieu, BAR-IS 1035 (Oxford: Archaeopress, 2002).

³² D. Jeffrey, “Experiential and Experimental Archaeology with Examples in Iron Processing,” *Institute for Archaeo-Metallurgical Studies Journal* 24 (2004).

discovering for oneself the workings of ancient technologies and understanding their application to everyday problems.”³³ By contrast, experimental archaeology “requires a rigorous scientific experiment intended to help determine the validity of a given hypothesis.”³⁴ It seems that Jeffrey believes that the experiential aspects of reconstruction have no value beyond the understanding that the individual gains through replicating processes. I do not believe that this is the case. The experience of performing a process can have implications for how a technology is used. A matter as simple as the ergonomics of a process, which are most effectively interpreted experientially, affects how the process is carried out and the roles of individuals involved in the process. This in turn has social implications.

For Brysbaert, replication provides a means for understanding the connections between people and the material.³⁵ In Brysbaert’s experimental replications of Aegean painted plasters, observation of the actor of a process (where the observer may also be the actor) can help us to “gain insights both into social aspects such as time use and management, labour input and decision-making (making choices), while interacting with the materials, and into mechanical aspects such as technical achievements and/or failures.”³⁶ She emphasises that replication provides some of the anthropological data which material analysis alone cannot provide. Essentially, Brysbaert brings the experimenter, his or her experiences and the experiences of observers to the forefront. However, Brysbaert’s approach is also empirical, incorporating sound background research to develop research questions and hypotheses, careful planning of experiments with consideration given to parameters and variables, and fair assessment of the outcomes.³⁷ As a result of her approach, Brysbaert was able to solve technological problems which could not have been solved otherwise.³⁸

Kelterborn and Jeffrey stress the importance of the skill of an experimenter for acquiring consistent results.³⁹ An unskilled experimenter has to deal with further variables which can mar the results because of his or her inexperience, although, if the skill of the experimenter is taken into account during the assessment of the results, experimentation might still yield useful results. However, when reconstructing craft

³³ Ibid., 13.

³⁴ Ibid.

³⁵ Brysbaert, “Does DIY Work?,” 11.

³⁶ Brysbaert, *The Power of Technology*, 66.

³⁷ Ibid., 68-76.

³⁸ Brysbaert, “Does DIY Work?,” 10.

³⁹ Kelterborn, “Principles of Experimental Archaeology.”; Jeffrey, “Experiential and Experimental Archaeology,” 13, 15.

practices, an experimenter cannot expect to obtain results similar to those of a master craftsman in antiquity if he or she has no experience in that craft. Likewise, the experimenter cannot expect to obtain useful results if he or she is experienced in the craft but has no background in archaeological method. Reconstructions by practitioners who are well-grounded in both fields are rare. Within archaeometallurgy I am able to cite only two scholars: Robert Baines, who has reconstructed Etruscan granulation techniques, and Herbert Maryon, who reconstructed a number of metallurgical techniques from antiquity, including the methods used to decorate some of the silver dishes of the late 4th-century AD Mildenhall Treasure.⁴⁰ Both made significant contributions to archaeometallurgical studies because they were able to replicate the methods skilfully, reducing the likelihood of chance results. Moreover, the reliability of their results depended on understanding the cultural and technological context of the crafts.

An essential point raised in the discussion of methodological approaches to experimental archaeology which must always be kept in mind is that successful results with a replicated process cannot prove that this process was used.⁴¹ Brysbaert explains that “experimental work can be seen *only* as a guide to understanding specific aspects of technology because we can never replicate the original cultural context in which people carried out their work....”⁴² This relates back to the point raised earlier that there are too many unknown variables. Successful experimentation, says Mathieu “merely eliminates possibilities, shows possible answers, and sometimes indicates the degree of probability of certain answers....”⁴³

The major theme which comes through all of the work discussed here is that variables should be limited as far as possible. This is somewhat achievable with careful planning which is based on solid background research leading to the development of hypotheses which are skilfully tested. Based on the recommendations of the various authors discussed here, I have adopted the following methodology: 1) experimentation must be based on sound background research; 2) a hypothesis should be developed as a basis for experimentation; 3) experimentation must incorporate repetition to reduce the

⁴⁰ R. Baines, “The Significance of Double-Row Granulation from Palestrina,” *Jewellery Studies*, no. 5 (1992); R. Baines, “The Reconstruction of Historical Jewellery and its Relevance as Contemporary Artefact” (RMIT University, 2005); H. Maryon, “The Mildenhall Treasure; Some Technical Problems: Part I,” *Man* 48 (1948); H. Maryon, “The Mildenhall Treasure; Some Technical Problems: Part II,” *Man* 48 (1948).

⁴¹ Coles, *Archaeology by Experiment*, 15, 18; Mathieu, “Introduction,” 8.

⁴² Brysbaert, “Does DIY Work?,” 11.

⁴³ Mathieu, “Introduction,” 8.

likelihood of chance affecting results; 4) results should be evaluated with acknowledgement of the limitations, especially choices of materials and the skill of the experimenter; 5) results should be reported honestly. This methodology has been applied in the present study.

Method

Stage One: Investigation of Minoan Vessels

The first stage is to investigate the corpus of extant Minoan metal vessels in order to discover what general processes were used in their manufacture, which then will indicate what specifics need to be investigated. This is carried out by examining previous publications about the vessels, especially those which catalogue and categorise them. In addition, an up-to-date list of extant vessels must be compiled. This will enable us to establish the shapes of the vessels, the metals they were made from, how they were constructed and their technical characteristics. These are covered in Chapter One, and the list of extant vessels is provided in Appendix 1.

Stage Two: Analysis of the Modern Vessel-Making Process

The second stage is to examine the process of metal-vessel making as it exists today in order to determine the basic steps required to transform a piece of metal into a vessel. This is necessary in order to understand how vessels are made in any period, what processes are used and what type of equipment is needed. This information will alert us to the technologies we need to identify in Minoan material in order to reconstruct the Minoan process. The modern process is described and discussed in Chapter Two.

Stage Three: Analysis and Evaluation of Previous Studies on Metal-Vessel Manufacture in the Bronze Age and Antiquity

The third stage is to evaluate previous theories about vessel manufacture in the Bronze Age and in antiquity. This is carried out with reference to the practical aspects of metalsmithing and to what has been established about vessel manufacture from stage two. This is covered in Chapters Three and Four.

Stage Four: Investigation of Minoan Metallurgical Equipment and Sites

In the fourth stage, Minoan metallurgical equipment is analysed with reference to the vessel-making process already explained. This is covered in Chapter Four, along with some evaluation of previous work on the topic.

Knowledge of the equipment needed opens up the question of identifying vessel-making locations. The most prominent Minoan metallurgical sites from the periods during which the surviving vessels were predominantly made are therefore investigated for evidence. These sites are listed in Chapter Five.

Stage Five: Examination of a Sample of Minoan Vessels

The next step is to examine personally a sample of Minoan vessels in order to discover what evidence the vessels themselves show of their manufacture. These examinations and the conclusions reached are described in Chapter Six.

Stage Six: Practical Reconstruction of Minoan Vessel-Making Methods using Replicated Equipment

After investigating all of the theoretical and observable evidence for the vessel-making process, the last stage is to replicate the equipment which appears to have been used for vessel manufacture and to test its feasibility for making vessels. These experiments are discussed in Chapter Seven. The specific details of the experiments undertaken are described in Part Two.

Stage Seven: A Reconstruction of the Minoan Vessel-Making Process

The last stage is to bring together all of the evidence produced in order to reconstruct the entire process. The implications of this study within a broader context are also considered. These are then presented in Chapter Eight, the conclusion.

A Summary of Minoan Culture and Chronology

Before we begin the study, I will briefly discuss chronological terms used here as well as the development of society in Bronze Age Crete, so that the general cultural context of the vessels can be understood.

The term Minoan is a modern label used to refer to Cretan peoples and culture during the Bronze Age. It is a convenient way in which to refer to the inhabitants, but we do not know what they called themselves. Furthermore, we cannot even be sure that the

inhabitants in the different regions of Crete identified themselves and their neighbours as a single culture or whether they regarded each other as being as foreign as the inhabitants of other islands, the mainland and further afield. However, throughout much of the Bronze Age, these different regions within Crete shared many cultural characteristics, including architecture, art, technology, society and religion. In these respects they exhibit some homogeneity as we look back on them and compare them with the inhabitants of Mainland Greece, whom we refer to today as Mycenaeans, the inhabitants of Cyprus and of some of the islands of the Aegean.

The changes which occurred in Crete during the Bronze Age are varied and complex. I will provide a brief summary of this history, since the changes which occurred are important in understanding the context of Minoan vessels. First, however, I will explain the chronological terms used.

Chronology and Chronological Terms Used in this Study

The Bronze Age in the Crete is traditionally divided into a tripartite system of Early, Middle and Late Minoan (EM, MM, LM), each of which was divided into three further parts, I, II and III. The resulting terms which were used to refer to periods consisted of labels such as EM I, EM II, EM III, MM I and so on. As scholars discovered further complexities in Minoan chronology, the terms became more complex, being broken into further subdivisions so that today we have terms such as LM IA and LM IIIA2. This system may be regarded as rather cumbersome, but it is a convenient way in which to refer to specific periods in the absence of reliable absolute dates. It is particularly useful for referring to chronological layers at Minoan sites and the artefacts which they contain. In this study, these terms are used when a site or an object has been dated in this manner by previous scholars. However, most general discussion in this study uses a different system which labels periods according to the system of the palatial development in Crete. These are extremely broad divisions which correspond fairly well to divisions within the tripartite system, although exactly where some of these divisions lie is debated. The terms are Prepalatial, Protopalatial, Neopalatial, Monopalatial and Postpalatial.⁴⁴ Some scholars use variations of these terms.⁴⁵ I have

⁴⁴ For a summary of the debate on the start of the Postpalatial period, for example, see L. Preston, "Late Minoan II to IIIB Crete," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 310-311.

⁴⁵ The Protopalatial is sometimes called the First Palatial Period, the Neopalatial the Second and the Monopalatial the Third Palatial Period.

chosen to use these terms because they are commonly used and easy to understand, once the development of Minoan culture is understood (see below).

An issue in chronology which is hotly debated but far outside the scope of this study is the absolute dating of these periods.⁴⁶ It will suffice to say here that there are two main systems in use: the low chronology, which is largely based on ceramic synchronisms with the well-established Egyptian chronology, and the high chronology, which is largely based on radiocarbon dating.⁴⁷ Absolute dates are rarely referred to in this study. For the reader's reference purposes, a chronology is provided in Table 1 showing approximate absolute dates in relation to the two systems of chronological terminology.

Table 1. Chronology of Bronze Age Crete with Approximate Absolute Dates

3100-3000	EM IA	Early Prepalatial
2900-2650	EM IB	
2650-2450/00	EM IIA	
2450/00-2200	EM IIB	
2200-2100/2050	EM III	Late Prepalatial
2100/50-1925/00	MM IA	
1925/00-1875/50	MM IB	Protopalatial
1875/50-1750/00	MM IIA-B	
1750/00-1700/1675	MM IIIA	Neopalatial
	MM IIIB	
1700/1675-1675-1625/00	LM IA	
1625/00-1470/60	LM IB	
1470/60-1420/10	LM II	Monopalatial
1420/10-1390/70	LM IIIA1	
1390/70-1330/15	LM IIIA2	
1330/15-1200/1190	LM IIIB	
1200/1190-1075/50	LM IIIC	Postpalatial

Source: Manning, "Chronology and Terminology," Tables 2.1 and 2.2. I have chosen to use the term Postpalatial rather than Manning's Final Palatial.

⁴⁶ For discussion see S. W. Manning, "Chronology and Terminology," in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2010).
⁴⁷ C. W. Shelmerdine, "Background, Sources and Methods," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 5.

The Development of Bronze Age Crete

The study of Minoan archaeology is dominated by the so-called palatial centres which were located at Knossos, Phaistos, Ayia Triada, Mal(l)ia, Galatas, Gournia, Zakros, Petras, Chania and probably near the modern city of Rethymno (**figure 1** and **figure 2**). Large, monumental structures at these locations served as centres of administration, trade, and religious practices. The most prominent of these is Knossos, which was the largest and probably most dominant of these throughout most of the Bronze Age. There is, however, a long history which leads up to the dominance of the palaces. Many of these sites seem to have been significant centres long before the palaces were built, and Knossos especially so. The periods with which this study is mainly concerned are the palatial periods: the Protopalatial, Neopalatial, Monopalatial and Postpalatial periods. These are the periods from which most Minoan vessels are extant and also from which the bulk of the relevant metallurgical artefacts are extant. We will begin here, however, with the Early Prepalatial period.

Early Prepalatial Period

By the Final Neolithic, the inhabitants of Crete had already developed numerous settlements, including large settlements at Knossos and Phaistos.⁴⁸ There are signs that by this stage metal items were already being produced, and that smelting of copper ores was taking place.⁴⁹ At this early stage, too, Cretans were already taking advantage of inter-regional and international contacts to import raw materials and finished goods.⁵⁰ International contact and trade was essential for the success of Crete because the island itself is lacking in many raw materials. Trade therefore played an important role throughout the Bronze Age.

At the start of the Early Prepalatial period, there was an influx of new settlers. The north coast shows evidence of Cycladic settlement, and for the Mesara the origins of the

⁴⁸ L. V. Watrous, "Review of Aegean Prehistory III: Crete from Earliest Prehistory through the Protopalatial Period," *AJA* 98, no. 4 (1994): 700.

⁴⁹ J. D. Muhly, "Chrysokamino in the History of Early Metallurgy," in *The Chrysokamino Metallurgy Workshop and its Territory*, ed. Philip P. Betancourt, Hesperia Supplements 36 (Princeton, N.J.: American School of Classical Studies at Athens, 2006), 155; P. P. Betancourt, "Discussion of the Workshop and Reconstruction of the Smelting Practices," in *The Chrysokamino Metallurgy Workshop and its Territory*, ed. Philip P. Betancourt, Hesperia Supplements 36 (Princeton, N.J.: American School of Classical Studies at Athens, 2006), 179.

⁵⁰ Watrous, "Review of Aegean Prehistory III," 701; P. P. Betancourt, "Minoan Trade," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 209-210.

settlers are unknown, though the technology and design of the pottery there indicates that settlers may have come from as far as Anatolia or elsewhere in the Near East.⁵¹

Over time, settlements and populations expanded, and there appears to have been a change from communal organisation to village-scale chiefdoms.⁵² Schoep explains that “social change during this period can be read as a progression away from a communal model of society, where households are subordinate to and regulated by higher-level or communal forms of organization, to one where the communal becomes subordinate to the interests of specific households, who take responsibility for the ongoing wellbeing of the community and become the main (elite) agents of socioeconomic development.”⁵³

These chiefdoms were strongly linked with each other, and there are signs of competitive emulation between elites with the conspicuous consumption of prestige goods.⁵⁴ Towards the end of the Early Prepalatial period, the first central courts, around which later palatial buildings were centred, were built at Knossos, Malia and Phaistos as well as other monumental buildings at Vasilike and Palaikastro.⁵⁵

Throughout this period, international contacts became increasingly sophisticated. Copper smelted from ore from the island of Kythnos and possibly from Lavrion on mainland Greece was being imported to produce items on Crete.⁵⁶ Other raw materials, including obsidian, gold, silver and rock crystal were being imported from the Cyclades, mainland Greece and the Near East.⁵⁷ Towards the end of the Early Prepalatial, connections with the north apparently ceased,⁵⁸ but trade with the east increased, and in addition to raw materials, luxury items from Egypt and western Asia were being imported.⁵⁹

In east Crete, destructions ended the EM IIB period, but the major centres west of Malia were apparently unaffected.⁶⁰ These destructions may be contemporary with destruction horizons in the Cyclades, on the mainland, in Anatolia and the Near East.

⁵¹ D. Wilson, “Early Prepalatial Crete,” in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 98.

⁵² S. W. Manning, “Formation of the Palaces,” in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 116.

⁵³ P. Tomkins and I. Schoep, “Crete,” in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2010), 76.

⁵⁴ Wilson, “Early Prepalatial Crete,” 99.

⁵⁵ *Ibid.*, 100; Tomkins and Schoep, “Crete,” 73.

⁵⁶ Wilson, “Early Prepalatial Crete,” 82-83, 86.

⁵⁷ *Ibid.*, 94.

⁵⁸ *Ibid.*, 96.

⁵⁹ Betancourt, “Minoan Trade,” 214.

⁶⁰ Manning, “Formation of the Palaces,” 109.

The causes of the destructions are unknown, but they may be connected to climate change and drought which occurred in the Near East and Egypt from c. 2200.⁶¹

Late Prepalatial Period

During EM III, there appears to have been an increase in the nucleation of populations, resulting in the growth of some settlements.⁶² By MM IA, strong trade contacts existed between Crete and Egypt, the Near East and Anatolia.⁶³ The result was an increase in the importation of prestige goods which, along with the introduction of burial styles which reflected individual status, indicate an increase in the levels of conspicuous consumption.⁶⁴ The appearance of Cretan Hieroglyphic probably reflects more complex administrative structures. By the end of the period there are signs of the formation of early states at some major centres, and Manning states that there is evidence of socio-political competition between the sites and regions.⁶⁵ Smelting activities at Chrysokamino suggest a complex system of industrial organisation which reflects the complexity of trade relationships and administrative control during this period. Smelting at Chrysokamino was only one link in a chain of copper production which involved metallurgical processes taking place at separate locations: the importation of ores, smelting at Chrysokamino and refining of the smelted metal elsewhere.⁶⁶

Protopalatial Period

At the start of the Protopalatial period, the first buildings which we call the palaces were built at Knossos and Phaistos, and monumental complexes appeared at other centres such as Malia and Petras.⁶⁷ In the case of Knossos and Malia, these were based on structures which were already present during the Prepalatial period.⁶⁸

International connections increased during the Protopalatial period. In particular, there was an increase in trade with Egypt with the importation of raw materials such as ivory, semiprecious stones, gold and wood, as well as other goods such as animals,

⁶¹ Wilson, "Early Prepalatial Crete," 98.

⁶² Manning, "Formation of the Palaces," 109.

⁶³ *Ibid.*, 110.

⁶⁴ *Ibid.*

⁶⁵ *Ibid.*,

⁶⁶ Betancourt, "Discussion of the Workshop and Reconstruction of the Smelting Practices," 181; P. P. Betancourt, "The Copper Smelting Workshop at Chrysokamino: Reconstructing the Smelting Process," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008), 110-111.

⁶⁷ C. Knappett, "The Material Culture," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 129.

⁶⁸ Tomkins and Schoep, "Crete," 73-74.

stone vessels and faience.⁶⁹ Importation of metals was apparently a high priority, and copper seems to have come from within the Aegean, while tin probably came from the Near East.⁷⁰ In addition, there are signs of increasing contacts in the southern Aegean at several locations, including Thera, Kythera, mainland Greece, Asia Minor and Rhodes.⁷¹

The palatial and monumental complexes incorporated public areas, such as courts and theatral areas, as well as exclusive areas such as residential quarters, dining halls and private courts. They also contained kitchens, storage facilities, archives and craft workshops, which seem to have supported the functions of the complexes. In addition, the monumental burial of individuals suggests the presence an elite class.⁷² The use of Minoan Hieroglyphic continues, and the Linear A script developed, apparently for administrative use.

These phenomena are said to reflect the degree of social stratification and centralised control.⁷³ There is no evidence to suggest that there was any king or powerful individual based within the palaces, but the design of the palaces suggests a distinct hierarchy.⁷⁴ Although some degree of broader, centralised control is indicated by state-run projects such as watch towers, roads, ocean-going ships, the construction of monumental buildings and sophisticated administrative systems, there was probably no extensive centralised control.⁷⁵ It has been suggested that, at this stage, Crete was divided into state-level polities, each with its own monumental centre surrounded by a large urban centre and dedicated external sites such as ports and peak sanctuaries (mountain-top shrines, several of which seem to have been associated with the monumental centres).⁷⁶

The role of crafts during this period is significant for this study. The inclusion of workshops within the palatial centres suggests that the goods produced were for consumption and control by the elite classes attached to these centres; these workshops may have been for artisans who were full-time specialists and were differentiated from craft workers making everyday utilitarian items.⁷⁷ As will be discussed later in §1.3, metal vessels, which are extant in larger numbers from the Protopalatial than the

⁶⁹ Betancourt, "Minoan Trade," 216.

⁷⁰ *Ibid.*, 215.

⁷¹ Knappett, "The Material Culture," 129.

⁷² Manning, "Formation of the Palaces," 112.

⁷³ *Ibid.*, 111.

⁷⁴ *Ibid.*, 119.

⁷⁵ *Ibid.*, 111-112, 119.

⁷⁶ *Ibid.*, 111.

⁷⁷ *Ibid.*, 112.

previous periods, may often be regarded as elite items which were restricted in their distribution. Consequently we might expect that these were usually produced in palace workshops.

Most of the Protopalatial settlements and palaces were destroyed by fire destructions at the end of MM IIB.

Neopalatial Period

After the MM II destructions, there was a burst of building activity across Crete. The Protopalatial palaces at Knossos, Malia and Phaistos were enlarged, with grander facades, spacious rooms, larger storage facilities and formal rooms.⁷⁸ New palaces were built at Zakros, Ayia Triada, Galatas and Petras, and probably also at Chania and near modern-day Rethymno.⁷⁹ Knossos remained the largest centre, and seems to have dominated cultural, religious and social spheres on the island, and probably also economic and political spheres; it is unclear whether Knossos administered the whole island, or whether the other palaces were autonomous.⁸⁰ Many smaller towns and villages existed throughout the island, as well as villas and farms. It has been proposed that at this time Crete was divided into a series of states, each of which consisted of a three-tier hierarchy with the larger palaces as primary centres, smaller palaces and towns as secondary centres and farm complexes and towns as tertiary centres. Younger and Rehak point out, however, that the findings do not neatly fit this pattern.⁸¹

Crafts flourished during the Neopalatial period, included pottery, metalwork (including vessels), masonry, frescoes, stone vases, ivory work, faience, woodworking and textiles. Almost all of these crafts originated from or before the Protopalatial period, but now increased in quality and complexity.⁸² As during the Protopalatial period, Neopalatial art seems largely connected with the palaces and large villas.⁸³ Raw materials and the production of luxury goods were apparently controlled under palatial administrations, which could limit distribution.⁸⁴

⁷⁸ J. G. Younger and P. Rehak, "The Material Culture of Neopalatial Crete," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 141.

⁷⁹ *Ibid.*, 141-142; E. Hallager, "Crete," in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2010), 151.

⁸⁰ Younger and Rehak, "The Material Culture," 152.

⁸¹ *Ibid.*, 150-151.

⁸² *Ibid.*, 154.

⁸³ P. Rehak and J. G. Younger, "Review of Aegean Prehistory VII: Neopalatial, Final Palatial, and Postpalatial Crete," *AJA* 102, no. 1 (1998): 111.

⁸⁴ *Ibid.*, 128.

Minoan art was very influential in the artistic traditions of mainland Greece and some of the Cycladic islands.⁸⁵ Many Minoan products also made their way abroad; a substantial number of Minoan art objects, including a large number of precious metal vessels, was buried in Grave Circles A and B at Mycenae during this period. The presence of Minoan art objects in these graves, and the presence of frescoes elsewhere, probably indicate the migration of Minoan artisans during this period.⁸⁶

Before the end of the Neopalatial period, in late LM IA, the nearby Thera volcano erupted, causing earthquake destructions and the abandonment of some sites. Far more significant fire destructions occurred later, at the end of LM IB, destroying administrative sites across the island.⁸⁷

Monopalatial Period

Although the LM IB fire destructions destroyed all major centres across the island, the central palace at Knossos remained standing and was partially rebuilt.⁸⁸ From this point, Knossos apparently became the administrative centre of the island. From this period we observe a strong mainland influence in Knossos. Minoan Hieroglyphs and Linear A are replaced by Mycenaean Linear B in administrative documents, and Mycenaean burial practices, pottery styles and iconography become prominent.⁸⁹ One school of thought suggests that Mycenaean elites controlled Knossos at this point, either having caused the LM IB destructions on the island or having taken advantage of internal political crises which resulted from the destructions.⁹⁰ Another school of thought proposes that, rather than indicating a Mycenaean takeover, the new Mycenaean influence may reflect mainland immigration to Crete.⁹¹

Outside Knossos, there were several other administrative centres which appear to have been secondary to Knossos, including Chania, Phaistos and probably Malia.⁹² Some crafts did not survive after the Neopalatial period, but those that did, including metal-vessel production, changed substantially.⁹³ Rehak and Younger believe that the

⁸⁵ Betancourt, "Minoan Trade," 217.

⁸⁶ Davis, *AGSW*, 332; Betancourt, "Minoan Trade," 217.

⁸⁷ Younger and Rehak, "The Material Culture," 140; Hallager, "Crete," 152-153.

⁸⁸ Younger and Rehak, "The Material Culture," 140; Preston, "Late Minoan II to IIIB Crete," 312.

⁸⁹ Preston, "Late Minoan II to IIIB Crete," 311.

⁹⁰ *Ibid.*, 311; Hallager, "Crete," 154.

⁹¹ Preston, "Late Minoan II to IIIB Crete," 312.

⁹² *Ibid.*, 313-314.

⁹³ P. Rehak, "Aegean Art Before and After the LM IB Cretan Destructions," in *TEXNH*, ed. Robert Laffineur and Philip P. Betancourt, *Aegaeum* 16 (Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1997), 56-57.

metal vessels found in graves in Crete and the mainland during this period were probably produced at Knossos.⁹⁴

Crete prospered at the start of LM III.⁹⁵ Betancourt considers this a result of the enhancement of production, particularly for foreign exchange.⁹⁶ International trade continued and apparently expanded. Raw materials and finished goods were imported from Cyprus, the Syro-Palestinian coast, mainland Greece, Anatolia and even from as far as Italy and further afield.⁹⁷ In addition, imported raw materials were being transformed into finished goods for export. Crete was at this stage well and truly part of an international trade network.⁹⁸

There was a major destruction of Knossos soon after the start of LM IIIA2. Knossos recovered and remained an important centre, but some other centres probably became independent at this stage.⁹⁹ During LM IIIB, the prosperity of Knossos and most large sites declined; by contrast, Chania seems to have flourished and reached a peak at this time.¹⁰⁰ Regionalism of pottery styles across the island indicates that outlying regions now became more independent. Metalwork also seems to become less homogeneous which, for Rehak and Younger, suggests there was no longer a single influential palatial workshop.¹⁰¹ There is disagreement about when Knossian administration of Crete ended, whether it was LM IIIA2 or LM IIIB; Preston concludes that there is now a greater consensus for LM IIIA2.¹⁰²

Postpalatial Period

With the end of palatial control over the island, by the end of LM IIIB all central sites on the island gradually suffered destructions or were abandoned.¹⁰³ As in the case of all of the previous Cretan destruction horizons, the causes are unknown, but it is possible that these last destructions were connected to political and economic crises in the Aegean and the Near East.¹⁰⁴ This reduction in the number of settlements probably indicates population shrinkage.¹⁰⁵ It appears that during LM IIIC populations moved

⁹⁴ Rehak and Younger, "Review of Aegean Prehistory VII," 157.

⁹⁵ Hallager, "Crete," 156-157.

⁹⁶ Betancourt, "Minoan Trade," 219.

⁹⁷ *Ibid.*, 220-222.

⁹⁸ *Ibid.*, 222.

⁹⁹ *Ibid.*, 220.

¹⁰⁰ Preston, "Late Minoan II to IIIB Crete," 318.

¹⁰¹ Rehak and Younger, "Review of Aegean Prehistory VII," 158.

¹⁰² Preston, "Late Minoan II to IIIB Crete," 310-311.

¹⁰³ *Ibid.*, 318.

¹⁰⁴ *Ibid.*, 318.

¹⁰⁵ Rehak and Younger, "Review of Aegean Prehistory VII," 166.

inland, away from the coasts; some settlements apparently were relocated further inland and several new settlements were established.¹⁰⁶ There were innovations in pottery, but most crafts ceased, and it seems that many items still in circulation were heirlooms from the previous period.¹⁰⁷ There is a marked regionalism in ceramics which reflects the decentralisation of control. Communities were probably autonomous and self-sufficient.¹⁰⁸

Bronze Age culture on Crete changed relatively peacefully into what is called Subminoan or Cretan Protogeometric, and the gradual appearance of iron tools and weapons marked the beginning of the Early Iron Age in Greece.¹⁰⁹

In this chapter, we have established what gaps exist in our current knowledge of Minoan metal vessels and how this study aims to fill these gaps. In the following chapter, we will become familiar with the extant vessels: their forms, features and materials, their possible uses and meaning, and the characteristics which distinguish Minoan vessels from those of contemporary cultures.

¹⁰⁶ Ibid., 167.

¹⁰⁷ Ibid., 169-170.

¹⁰⁸ S. Deger-Jalotsky, "Decline, Destruction, Aftermath," in *The Cambridge Companion to the Aegean Bronze Age*, ed. Cynthia W. Shelmerdine (Cambridge: Cambridge University Press, 2008), 403.

¹⁰⁹ Rehak and Younger, "Review of Aegean Prehistory VII," 171-172.

Part One

The Thesis

Minoan Metal Vessels

Minoan metal vessels come in a large range of shapes with a variety of features. In this chapter, the various types and their features are dealt with in detail. The first section sets out the difficulties associated with establishing a reliable chronological sequence for the vessels and summarises the development of the vessels through the periods of Bronze Age Crete based on the extant vessels. The second section describes the vessel types, their features – handles, rims, legs etc. – and the alloys used. The possible uses and social significance of metal vessels in Crete are then discussed and, finally, some observations are made about the characteristics of Minoan vessels within the context of the broader region. After this introduction to the vessels themselves, we will be able to move on to the techniques of metal-vessel production in Chapter Three.

§1.1. The Development of Minoan Metal Vessels

§1.1.1. Issues Affecting the Interpretation of the Minoan Vessel Corpus

Several matters make it difficult to generalise about the development of Minoan vessels. It is clear, as Matthäus states, that the extant material represents only a small percentage of the number which would have been in circulation.¹¹⁰ The number of extant and identifiable bronze vessels known to date is only 237 and precious-metal vessels only 14. Many vessel forms exist only as one or two examples.

A major reason for the low numbers would be the fact that many vessels would have been melted down. This may have happened when they were no longer functional or when the material was wanted for other uses – manufacturing weapons during times of conflict is one example. Much recycling may have happened in later periods, especially during the relatively destitute periods following the Bronze Age. Another factor which might skew our interpretation of the chronology of vessel types is the fact that, since metal is so durable, some vessels may have been retained for a century or more before their deposition.¹¹¹

¹¹⁰ Matthäus, *BKMK*, 59.

¹¹¹ Catling, *CBMW*, 187.

One of the most significant reasons why it is not possible to construct a complete typology of the vessels is that the vessel corpus is severely affected by differences in deposition. Vessels are only found in settlements when a sudden destruction has occurred.¹¹² Matthäus believes that this means that the selection of vessels from any one period is relatively random. In addition, Matthäus says, the number of finds is practically synonymous with the number of destructions and, as such, the corpus is skewed in favour of those periods during which major and sudden destructions occurred. This would account for the LM IB period appearing to be relatively rich.

The other main type of deposition in which vessels are found is the grave. Once again, the vessels represented are not necessarily representative of the entire corpus, since the vessels inhumed could have been deliberately selected in accordance with various beliefs and burial practices.¹¹³ The matter of burial practices is in fact important, since burial customs changed significantly in Crete during the Bronze Age. Data compiled by Matthäus indicate that during MM all metal vessel finds are from settlements and none from graves. During the Neopalatial period, settlement finds represent 95% and graves 5%. During the Monopalatial period, when Cretan burial customs were heavily influenced by Mycenaean customs, settlement finds represent only 3% and grave finds 97%. During the Postpalatial period, 15% are settlement finds and 85% grave finds.¹¹⁴ Considering the large spans of time during which people were not burying vessels as grave goods and during which there were no destructions so significant that the vessels could not later be retrieved, it is clear that a vast amount of material is missing. Matthäus proposes that the reason why so few vessels remain from MM is that they were recovered and re-entered circulation during the rebuilding which occurred at the start of the Neopalatial period.¹¹⁵

Yet another matter which complicates our understanding of the Minoan tradition is the presence of Minoan vessels on the mainland. It is clear that the Mycenaean vessel tradition was heavily influenced by the Minoan tradition, to the extent that they are considered the same tradition, since many forms and techniques are shared.¹¹⁶ By Matthäus's figures, the Mycenaean bronze vessel corpus represents 64% of the extant vessels from the combined traditions, and Minoan only 33%, while the islands represent

¹¹² Matthäus, *BKMK*, 61.

¹¹³ *Ibid.*, 61.

¹¹⁴ *Ibid.*, 62.

¹¹⁵ *Ibid.*, 64.

¹¹⁶ Catling, *CBMW*, 187.

3%.¹¹⁷ This bias would be due to Mycenaean burial practices which involved the inhumation of many vessels, especially precious-metal ones, as burial gifts. Between Late Helladic I and IIIA (synchronous with LM I to IIIA), grave-finds make up almost 100% of the metal vessel corpus, and from Late Helladic IIIB to the Sub-Mycenaean period, 70% are from hoards.¹¹⁸

It is difficult, however, to distinguish which vessels from mainland deposits are of the local tradition and which Minoan. Davis identifies a number of features on precious-metal vessels which she uses to distinguish between vessels of Minoan and Mycenaean manufacture.¹¹⁹ She also uses these to identify vessels which were either made by Minoan smiths working for Mycenaean patrons or by Mycenaean smiths trained by Minoans. Using this system, she identifies 72 precious-metal vessels out of the 149 she catalogues from Crete and the mainland as being of Minoan manufacture and only 38 of Mycenaean manufacture.¹²⁰ Of all the vessels she lists, only 14 are actually from Crete. If Davis's theories are correct, we are missing a huge amount of the Minoan corpus of precious-metal vessels, since we ought to expect many more precious-metal vessels to have been in circulation in Crete.

Account must also be taken of the skeuomorphic features of metalware apparent on some ceramic vessels. Some of the metallicising features often referred to include imitation rivet-heads, lustrous glazes or burnishing, thin fabric, high, strap-handles, high spouts and fluted rims.¹²¹ Ceramic vessels with these features are sometimes cited as reflecting metal forms which were in circulation at the same time but which are no longer available to us.¹²² A study of such vessels might provide information on the corpus of missing metal vessels. However, some features which are referred to as metallicising are questionable. The fine fabric of MM IB eggshell ware, which is sometimes thought to imitate metal forms, appears with the development of the potter's wheel, which enabled potters to make thinner walls than ever before.¹²³ This development may have been not so much an imitation of metal as an attempt by potters to exploit the new technology. The presence of high spouts on EM vessels is probably

¹¹⁷ Matthäus, *BKMK*, 61.

¹¹⁸ *Ibid.*, 62.

¹¹⁹ Davis, *AGSW*, 328-352.

¹²⁰ *Ibid.*, 352-355.

¹²¹ e.g. A. J. Evans, *The Palace of Minos at Knossos*, vol. 1 (London: Macmillan, 1921), 80, fig. 47a; G. Nakou, "Absent Presences: Metal Vessels in the Aegean at the End of the Third Millennium," in *Metallurgy in the Early Bronze Age Aegean*, ed. Peter M. Day and Roger C. P. Doonan (Oxford: Oxbow Books, 2007), 229-231.

¹²² Nakou, "Absent Presences," 231.

¹²³ P. P. Betancourt, *Vasilike Ware: An Early Bronze Age Pottery Style in Crete*, vol. 61, *SIMA* (1979), 77-79.

an imitation of gourd-vessels, which are naturally inclined to this shape.¹²⁴ Lastly, fluted rims on ceramic vessels are often thought to imitate the fluting which occurs during early stages of metal-vessel production.¹²⁵ However, fluting also occurs on ceramic vessels being made on a wheel. Clearly, these metallicising features must be more carefully considered before any conclusions are drawn about skeuomorphic reflections of missing metal vessels.

§1.1.2. A Tentative Chronology of Minoan Vessel Development

Considering the issues raised in the previous section, it seems unwise to attempt a chronology of vessel development. However, there appear to be some broad patterns which may be useful for interpreting the vessel corpus. Future vessel finds may (and hopefully will) change this interpretation. The following summary is based on the list of extant vessels in Appendix One. Type numbers cited here are from Matthäus's typology of bronze vessels.¹²⁶ These are discussed in further detail in §1.2.1, but, for quick reference, a list of these types can be found at the beginning of Appendix One.

Prepalatial

The only Prepalatial vessels known from Crete are two silver cups from Mochlos, both found in EM II-III contexts.¹²⁷ Davis says that there is not much evidence that vessels in gold and silver were being produced in Prepalatial Crete.¹²⁸ Silver vessels from Byblos and the Tôd treasure which are contemporary with EM appear not to have Minoan origins as was once thought.¹²⁹ No copper or bronze vessels are extant.

Protopalatial

Nine vessels are extant from Protopalatial contexts. One of these is an unusual MM IB lobed silver kantharos from Gournia. Bronze vessels first appear in MM II levels. The forms are basic tripod cauldrons with three handles, a flat tripod pan with two handles, basins with two handles and a bowl with two handles.¹³⁰ These initial forms all continued to be produced for some time. In the case of tripod vessels, the form

¹²⁴ Ibid., 30.

¹²⁵ E. N. Davis, "The Silver Kantharos from Gournia," *TUAS* 4 (1979).

¹²⁶ Matthäus, *BKMK*.

¹²⁷ Davis, *AGSW*, 95, n. 265 and no. 11.

¹²⁸ Ibid., 86.

¹²⁹ Ibid., 69-85.

¹³⁰ *BKMK* types 5, 49C, 10A, 46C.

continued in some form until the start of the Geometric period. Two-handled basins continued to be produced until the end of the palatial periods.

Neopalatial

In Neopalatial levels, the number, variety and complexity of forms increases dramatically. Two-handled basins and tripod cauldrons continue, though the shapes of the latter are more refined, and we see a large number of new forms: one-handled basins, gigantic cauldrons, hydrias, pitchers, cups, pans, ladles, braziers, sieves, lamps, and lekane precursors amongst others.¹³¹ Five silver vessels come from Neopalatial contexts,¹³² and many of the precious-metal vessels on mainland Greece from this period - especially from the Late Helladic I Mycenaean Shaft Graves - are regarded as being of Minoan manufacture.¹³³ The techniques used are more complex than in the preceding period, including handles and legs which are cast instead of being hammered from billets, and decoration appears on bronze vessels for the first time, such as on one-handled basins with relief-decorated cast rims and handles, and hydrias with repoussé-decorated shoulders.¹³⁴

Monopalatial Period

After the LM IB destructions and the beginning of the Monopalatial period, bronze vessels continue to be produced, but there are several changes.¹³⁵ Forms which continue include the two-handled basins, hydrias, with minor changes, pans, braziers and tripod cauldrons.¹³⁶ The gigantic cauldrons disappear, as do sieves and large pans with vertical hollow handles, and some forms, noticeably the one-handled bowls with relief-decorated rims and handles almost completely disappear.¹³⁷ Many older forms evolve. Lekanai acquire two handles and sometimes spouts, some basic bowls have dropped bases, lamps change slightly, and some pans now have legs.¹³⁸ Some new forms appear such as several different pitcher-type vessels, kylikes, and small pans with solid vertical handles.¹³⁹ Relief-decoration on vessels appears to decline after LMIB,¹⁴⁰

¹³¹ *BKMK* types 32, 1A, B and C, 20, 30, 33, 38B, 13A, 4A and B, 57C, 59A, 60, 58A, 44.

¹³² Davis, *AGSW*, nos 13-17.

¹³³ *Ibid.*, 353-355.

¹³⁴ *BKMK* types 32E and 22.

¹³⁵ Rehak, "Aegean Art Before and After the LM IB Cretan Destructions," 56-57.

¹³⁶ *BKMK* types 10A, B and , 21, 4A and B, 59A and 6.

¹³⁷ *BKMK* types 1A, B and C, 60, 13A and 32, 32A, B, C, D and E.

¹³⁸ *BKMK* types 45A1, A2, B1 and B2, 50, 51, 58A and B and 4A and B.

¹³⁹ *BKMK* types 24 to 29, 31, 43 and 15.

¹⁴⁰ Rehak, "Aegean Art Before and After the LM IB Cretan Destructions," 57.

although, since most of the Neopalatial decorated vessels are the relief-decorated one handled bowls,¹⁴¹ which disappear during this period, this may not be indicative so much of a decline in decoration as a decline in demand for this type of vessel. Some decoration was still carried out, but the designs appear to be less figurative than earlier.¹⁴²

Rehak reports that only 27% of extant, dateable precious-metal vessels in the Aegean date to a period after LMIB, and proposes that some still in circulation at this time were probably heirlooms from earlier periods.¹⁴³ Other crafts at this time also decline or disappear and others replace them, probably reflecting the new Mycenaean influence in Crete.¹⁴⁴

Postpalatial

A number of bronze vessels come from Postpalatial contexts, but many of these may be heirlooms from earlier periods.¹⁴⁵ However, some potential evidence for tripod production at LM IIIB or C Palaikastro, discussed in §5.9, indicates that the practice was not completely lost.

§1.2. Minoan Vessel Types and Characteristics

§1.2.1. Vessel Types

For this study, a database of published bronze and precious-metal vessels was compiled. An abbreviated version of this database can be found in Appendix 1. Vessel types are listed below according to their basic shapes. Individual features such as rims, handles, legs, spouts and bases are described in detail in §1.2.2. Type numbers referred to are those of Matthäus's typology in *BKMK*. A list of the types can be found at the beginning of Appendix 1. Since Matthäus has already described in detail the variations between these types, rather than repeating this here, the reader is referred to his work for further subcategories of these shapes. Although many vessels from mainland Greece and some of the islands show signs of being of Cretan manufacture, only vessels found on Crete are discussed here and others are mentioned where relevant. Although Davis

¹⁴¹ *BKMK* type 32E.

¹⁴² e.g. Matthäus, *BKMK*, no. 464.

¹⁴³ Rehak, "Aegean Art Before and After the LM IB Cretan Destructions," Appendix and 57.

¹⁴⁴ *Ibid.*, 62.

¹⁴⁵ *Ibid.*, 57.

provides compelling arguments for identifying many precious-metal vessels from the mainland as Minoan work, and some of these are no doubt correct, I believe that there are simply not enough metal vessels extant to draw strong conclusions on typological or technical matters.¹⁴⁶

Cauldrons: BKMK Types 1A, 1B and 1C (figure 3)

These round-based, two- or three-handled cauldrons, the largest of the Minoan vessels, range in diameter from at least 400 to 1250 mm. They are constructed from several pieces of sheet joined with rivets at the seams, typically three horizontal sections comprising the base, walls and rim. The base is a single round and concave piece of sheet, the wall section several sheets joined end-to-end and the rim one or two long and narrow strips joined end to end. The rims are out-turned or T-section.

Cauldrons over 500 mm in diameter are found only in Crete. Smaller cauldrons made in a similar fashion are found amongst the Mycenaean material as well as smaller cauldrons formed from a single sheet and with walls which are carinated either above or below the centre of gravity. Sherratt and Taylor cite carinated cauldrons in contemporary Byblos as evidence of interaction between the Aegean and the Levant during this period.¹⁴⁷

Tripod Cauldrons: BKMK Types 5, 6, and 7A

Three-legged cauldrons have two or three handles on or just below the rim, the latter often with a shallow spout on the rim. They range from 250 to 610 mm in diameter and 200 to 600 mm in height. There are three different types which occur at different stages and reflect stylistic and technological developments. Type 5 (figure 4), which appears at the end of the Protopalatial period, has a simple hemispherical body, a plain rim, simple rod-legs and vertical loop-handles. Type 6 (figure 5), which occurs during the Neopalatial period, has a curved base and straight, vertical or slightly everted walls. They are usually made from a single sheet, though multi-piece bodies also exist. The rim is folded out and the handles, fitted just below, are horizontal. On some three-handled cauldrons, a loop is attached to the rim in lieu of the third handle (figure 6). The handles and legs have attachment-plates by which they are riveted to the vessel.

¹⁴⁶ Davis, *AGSW*, 328-356.

¹⁴⁷ A. Sherratt and T. Taylor, "Metal Vessels in Bronze Age Europe and the Context of Vulchetrun," in *Thracians and Mycenaeans: Proceedings of the Fourth International Congress of Thracology, Rotterdam, 24-26 September 1984*, ed. Jan G. P. Best and Nanny M. W. De Vries (Leiden: Brill, 1989), 110-111.

The rivets are in many cases decoratively formed, with a large mushroom-head on the inside. The legs are more solid than those of the Protopalatial precursor.

Type 7A (**figure 7**) has a rounded base and walls, a vertical rim and vertical ring-handles, and the leg attachment-plates sit higher on the body than those of Type 6. Type 6 seems to be found only in Crete, where it is quite common, and Type 7A is more common on the mainland. The few of these which do appear in Crete date to LM IIIA1 during the Mycenaean presence in Crete. These factors indicate that the curved Type 7A, as well as the similarly-shaped Types 7B and 8, which are not found on Crete, were probably Mycenaean forms. Catling regards Type 7 cauldrons as a technical advancement on Type 6.¹⁴⁸

Pans: BKMK Types 4A, 4B, 4: Varia, 9 and 12

There are several different pan types. Type 4A pans (**figure 8**) have a flat base and straight, vertical or slightly everted walls. The rim is usually folded out, though one extant has a rolled rim. They are broad and shallow, ranging from 300 to 400 mm in diameter and 65 to 180 mm in height, and have two riveted-on horizontal handles with attachment-plates. Type 4B (**figure 9**) is similar to 4A but has three small riveted-on cast feet which raise the base slightly. Neither type is found on the mainland. A single pan with wishbone-handles from LM IIIB Zapher Papoura has been recovered, but it is uncertain if this form is genuine or a result of modern reconstruction. Matthäus has categorised it and a handful from the mainland as a variety of Type 4.¹⁴⁹

Type 9, only one of which is extant, from MM II Malia Quartier Mu, is a low pan with two handles and three tall legs riveted to the wall. Two others come from the mainland, dated LH I and LH IIIA.¹⁵⁰

Type 12 (**figure 10**) has a rounded base and walls which bulge out at the base and narrow towards the rim. The rim is plain and the handles are wishbone-types. The two examples which exist date to LM IIIA1. It does not occur elsewhere. Matthäus lists these separately from type 4 forms and Catling lists them together.¹⁵¹

Two-Handled Basins: BKMK Types 10A, B, C and E

These broad, shallow basins (**figure 11**) have flat or slightly-curved bases and two vertical or everted loop-handles. Smaller-sized basins range from 220 and 320 mm in

¹⁴⁸ Catling, *CBMW*, 169.

¹⁴⁹ Matthäus, *BKMK*, 99-100.

¹⁵⁰ *Ibid.*, nos 103, 104.

¹⁵¹ Catling, *CBMW*, 170-171.

diameter and 45 to 85 mm in height and larger sizes between 440 and 650 mm in diameter and 100 to 150 mm in height. They occur in Crete from the Protopalatial period until the end of the Monopalatial period and vary in rim design - thickened, folded, or with relief decoration - and in the construction of the handles, which may be bent rod, rod with flattened attachment-plates or cast with relief decoration (**figure 12**). They are found on the mainland from LH IIIA and in Cyprus from LC. The Cypriot basins are presumably of local manufacture and reflect the strong Aegean influence on Cypriot vessel-making brought about by the arrival of Aegean settlers.¹⁵² One Cypriot example has a dropped base, which is unknown in Aegean basins. Catling notes its suitability for use on a stand.¹⁵³

Small Pans with a Single Vertical Handle: BKMK Type 15 (figure 13)

These small, shallow pans, between 100 and 150 mm in diameter and 20 to 35 mm in height, have a single, solid rod-handle rising 75 to 85 mm vertically from the rim. The entire vessel, body and handle, is made from one piece of metal. The rims are flat, sometimes with relief decoration on the upper surface. They occur on both Crete and the mainland from LM/LH IIIA. Some mainland vessels have relief-decoration on the handles, and one mainland vessel, which Matthäus distinguishes as a separate type, has a hollow handle.¹⁵⁴

Large Pans with a Single Vertical Hollow Handle: BKMK Type 13A (figure 14)

Identical in form to the previous pans described, these pans are larger and their handles hollow. Their bodies range from 260 to 270 mm in diameter and 55 to 65 mm in height with handles rising 72 to 85 mm above the rim. The two of these pans from Crete are dated to the Neopalatial period and several from the mainland are contemporary.

It is presumed that the handle is hollow because there was a wooden handle to be fitted into it.¹⁵⁵ If this is the case, this may indicate that whatever the use of the vessel was, it caused the pan to become hot. This would support Catling's suggestion that these were lamps. One wonders how the wooden rod was held fast, since there are no holes in the socket for nails to fix the handle in place. It is difficult to know whether these pans are related to the smaller Type 15 pans. Catling places them in the same

¹⁵² Ibid., 147, 153, 188.

¹⁵³ Ibid., 153, no. I.1.

¹⁵⁴ Matthäus, *BKMK*, no. 174.

¹⁵⁵ Catling, *CBMW*, 183.

category as lamps with vertical handles whereas Matthäus separates them. The difference in their sizes indicates that they probably had different uses.

Bowls: BKMK Types 47A, 49B, 50 and 51

There is a small range of bowls in a variety of shapes. They are gathered together here only because the description of bowl seems the most apt. Whether their functions were related is another matter. Type 46, of which only one badly-fragmented MM II example is extant, is a two-handled bowl. The handles are attached to the wall by rivets and the rim is slightly thickened. Type 47A (**figure 15**) are plain, hemispherical bowls with plain rims. Vessels of this shape represent the most basic vessel-forming skills, and are probably the first vessel form created by metalsmiths. Most vessels, no matter how complex, must in their early formation-stages take this simple hemispherical form. Only two bronze bowls of this type exist in Crete, dated to LM IB and LM II. An EM II-III silver bowl from Mochlos may be of the same type.¹⁵⁶ On Cyprus, bronze hemispherical bowls are numerous after the mid-thirteenth century. Catling suggests that the form may have come to Cyprus from the Near East, though the form was also uncommon there.¹⁵⁷ The hemispherical bowl was used to create two one-handled cups in silver which were found in Cyprus. These two are usually attributed to Minoan or Mycenaean workmanship because one is skilfully inlaid, a technique which was mastered by Aegean smiths, and because both have the wishbone-style handles found on several Aegean forms.¹⁵⁸

Only one example of Type 49B exists (**figure 16**), dated LM IB. The junction of the base and wall is rounded and the diameter narrows towards the rim, which is folded down the outside of the wall.

Type 50 (**figure 17**) is a shallow bowl with a dropped foot. The four Cretan examples are Monopalatial and range in diameter from 100 to 150 mm. The rims are lightly or heavily thickened and the walls straight or slightly curved. One also has a cast attachment riveted to its wall which appears to have been a hinge.¹⁵⁹ This form is also found on the mainland. Three LM IB silver bowls, one with repoussé spiral decoration, are comparable with Type 50.¹⁶⁰

¹⁵⁶ Davis, *AGSW*, no. 11.

¹⁵⁷ Catling, *CBMW*, 148.

¹⁵⁸ Ibid., 46; Davis, *AGSW*, 320-321; R. S. Merrillees, "Metal Vases of Cypriot Type from the 16th to 13th Centuries B. C.," in *Early Metallurgy in Cyprus, 4000-500 B.C.*, ed. James D. Muhly, Robert Maddin, and Vassos Karageorghis (Nicosia: Pierides Foundation, 1982), 246.

¹⁵⁹ Matthäus, *BKMK*, no. 431.

¹⁶⁰ Davis, *AGSW*, nos 15, 16, 17.

Only one example exists of Type 51 (**figure 18**), a bowl with everted walls, narrow base and a plain rim dated to LM IIIA1. It is 75 mm high and its rim is 148 mm in diameter. Catling classes it as a handleless cup.¹⁶¹

Hydrias and Related Forms: BKMK Types 20, 21, 22A, 24 and 27

These forms are categorised under separate types by both Matthäus and Catling according to the variations between shapes. Overall, these types have piriform bodies with short, narrow necks and a narrow base. The types vary in size, the shape of the rim and base, the number of handles, the presence or absence of decoration and the number of wall sections that make up the body of the vessel.

Types 20 (**figure 19**) and 21, large hydrias, are fairly uniform in their basic shape. They have out-turned rims, a vertical strap-handle connecting the rim to the shoulder and a smaller horizontal handle below the shoulder. The top of the upper handle often has a small knob adjacent to the rim, which may have been a help in grasping the handle while pouring. They range in height from 350 to 600 mm and the bodies are composed of three or four horizontal sections of sheet riveted at the seams. They are usually undecorated, though two have shell forms incorporated into the upper handles. Type 20 occurs during the Neopalatial period and 21 during the Monopalatial period.

Matthäus and Catling categorise separately some piriform vessels which are of similar size to Types 20 and 21 but decorated and with no lower handle.¹⁶² Type 22A (**figure 20**), of which only one identifiable example is extant from Crete, has repoussé decoration on the shoulder and torus-moulding on the neck; the rim is rolled outwards and around a copper ring. Type 24 (**figure 21**), of only two sections, has a relief-decorated band masking the seam between the neck and shoulder sections. Only a handful of decorated piriform vessels have been recovered from Crete, but several remain from the mainland, including one similar to Type 22A in silver which Davis says is made from one sheet.¹⁶³ These appear during the same periods as the plain hydrias. Type 27 (**figure 22**), which has a bird-head shaped protome attached to the rim, has a wider mouth than the hydrias.

¹⁶¹ Catling, *CBMW*, 181.

¹⁶² *Ibid.*, 177-178, forms 14 and 15; Popham, Catling, and Catling, "Sellopoulo," 236, no. 30, fig. 23.30.

¹⁶³ Davis, *AGSW*, no. 43.

One-Handled Basins: BKMK Types 32A, B, C, D and E

These large, shallow basins range from 260 to 390 mm in diameter and 45 to 95 mm in height. They have a dropped foot and a wide loop-handle which rises up and out from the rim and ends on or near the middle of the wall. There are three main categories. Type 32A (**figure 23**) is made entirely from one piece of metal. The rim is heavily thickened and occasionally ornamented with relief decoration. The handle may also be decorated. Types 32B, C and D have a separate handle attached on or just below the rim with rivets. The rim of 32B is widened as for 32A, while those of 32C and D (**figure 24**) are rolled around a ring of lead or copper. Form 32E (**figure 25**) is the most elaborate, with a separately-made, relief-decorated rim and handle riveted to the body. One-handed basins are numerous during the Neopalatial period, but they number very few afterwards. Several of these basins come from the mainland in precious metals.¹⁶⁴ A far more elaborate variation is found in the shaft graves at Mycenae. These are in precious metals and frequently have very complex repoussé decoration on the body.¹⁶⁵

Cups: BKMK Types 33, 35, 37C and D, 38B, 40 and 43

There are several different cup types in both bronze and precious metals. Type 33 (**figure 26**) has a shallow bowl-shaped body with a dropped foot, and the handle, which is of the same piece of sheet as the body, is a simple strap form which rises up in a loop from the rim. The end of the handle may or may not be attached to the body by a rivet. Cups of this form in gold and silver are also found in Crete, one decorated with repoussé.¹⁶⁶ One in silver comes from Prepalatial Mochlos,¹⁶⁷ but the other bronze and precious-metal cups date to the Neopalatial and Monopalatial periods. They are also found on the mainland over a similar period. Davis notes predecessors for this type in finds from Ur, Central Anatolia and the Tôd treasure, and proposes that the form may have already been adopted in Crete by the end of EM.¹⁶⁸

Types 35 (**figure 27**) and 37C and D (**figure 28**) have curved walls, flat-bases and a separate handle attached at the rim and part-way down the wall. Type 35 also has a spout. These forms are quite uncommon in both Crete and the rest of Greece.

Type 38B (**figure 29**), usually referred to as the 'Vapheio' cup after the two famous gold cups of this form from Vapheio on mainland Greece, has straight, everted walls, a

¹⁶⁴ e.g. *ibid.*, nos 46, 107.

¹⁶⁵ e.g. *ibid.*, nos 110, 116.

¹⁶⁶ *Ibid.*, nos 18-20.

¹⁶⁷ *Ibid.*, 95, n. 265.

¹⁶⁸ *Ibid.*, 108-109.

flat base and a single spool-handle riveted to the rim and wall. One complete bronze cup of this type comes from LM IB Mochlos. A bronze spool-handle comes from Neopalatial Tylissos, and an undated copper cup inlaid with gold, silver and electrum and reported to come from Crete may be of this type, though the handle is missing (**figure 30**). Several cups of this form in precious metals come from the shaft graves at Mycenae.¹⁶⁹ A similar type with a strap-handle instead of the spool-type exists in large numbers on the mainland in precious metals, largely from the shaft graves at Mycenae, and are frequently decorated with elaborate repoussé patterns.¹⁷⁰ This type does not appear in Crete in metal, though its pottery parallel is found from EM II until LM IB. A cup of Type 38B from Cyprus made from silver is generally accepted to be of Aegean origin.¹⁷¹ In Crete, the spool handle is found only on this vessel type, though it is found on two other mainland cup types in gold and electrum.¹⁷² Davis argues for a stylistic difference between Minoan and Mycenaean spool handles, though this conclusion is based on only a small number of examples from Crete.¹⁷³ The spool handle probably originates in Anatolia, where it is found on several vessels which predate Aegean examples.¹⁷⁴

The kylikes, Type 43 (**figure 31**), are quite different from the other cup types. The bowl of the cup is mounted on a high stem rising from a flat foot, and two handles are set on opposite sides on the rim. The stem and foot are sometimes made of a separate piece of metal from the bowl, and the foot is weighted for stability. Only one complete Cretan example is known, made from bronze and dating to LM IIIA1. Unfortunately, there is little known about this vessel's construction. A Postpalatial cast foot or foot-core from this vessel type is also extant. A fragmentary silver kylix from LM II-III A Isopata exists, and a similarly-shaped silver goblet from Knossos of the same period has one relief-decorated gilded copper strap-handle and rim.¹⁷⁵ On the mainland, kylikes and one-handled goblets are more numerous, though they occur only in precious metals, often decorated with repoussé.¹⁷⁶

Mention should also be made here of a silver lobed kantharos from Protopalatial Gournia (**figure 32**). This vessel is quite unlike any other in the Minoan tradition, with

¹⁶⁹ Ibid., nos 38-42, figs 115-118.

¹⁷⁰ e.g. ibid., nos 25-28, figs 98-104.

¹⁷¹ Catling, *CBMW*, 46; Davis, *AGSW*, 320-321; Merrillees, "Metal Vases of Cypriot Type from the 16th to 13th Centuries B. C.," 246.

¹⁷² Davis, *AGSW*, 183-187, no. 63, figs 148-150 and 208-221, no. 83, figs 172, 173.

¹⁷³ Ibid., 43-50.

¹⁷⁴ Ibid., 72-73.

¹⁷⁵ Ibid., nos 21 and 22.

¹⁷⁶ e.g. ibid., nos 52, 82, 123.

a narrow base expanding to a carinated shoulder and fluted rim, and two strap-handles. Davis argues that it is of Minoan manufacture inspired by Anatolian forms.¹⁷⁷ If it is of Minoan origin, it is an anomaly amongst Minoan metal vessels, since the level of complexity in its construction, especially the carinated body and fluted rim, is not seen in any other vessel. This may indicate that the tradition in Crete at this stage was more developed than extant vessels indicate.

Pitchers and Other Pouring Vessels: BKMK Types 25, 26, 28, 29, 30, 31 and 40

Pitchers and other pouring vessels come in several different types. Types 25 and 26 (figure 33) are similar in form to the hydrias described above, but are far smaller at 200 to 220 mm high, have only an upper handle, and are made from only two sections. There are two Cretan examples extant, both dated to LM IIIA1. One of Type 25 from the mainland is made from a single sheet.¹⁷⁸

Type 28 (figure 34) has a flat base, rounded body, a flat, everted rim, and a strap handle. Only two in bronze are extant from Crete, 95 and 125 mm high, both dating to LM IIIA1. Another from the mainland dates to LH IIIB.¹⁷⁹ The two Cretan vessels might be cups, given their size, but the mainland vessel, at 154-156 mm high, seems too large to be a cup.

Type 29 (figure 35), only one of which is extant, has a rounded body, splayed foot, long, narrow neck, and its rim is rolled out around a ring. Its rod-handle is riveted to the vessel just under the rim and where the wall bulges out from the narrow neck. It is 314 mm high and is dated to LM IIIC. Between the upper part of the body and the foot, the vessel has been reconstructed in plaster, so it is unclear whether it was made from a single piece of metal or two. It is likely, given the construction methods of all other Minoan closed vessels, that it was made from two parts. The only other closed one-piece vessels which have survived are two precious-metal pitchers. One of these, 116 mm high, is of silver and has a high spout (figure 36). The other, of silver with gold and electrum overlays and tiny at 68 mm high, is quite damaged, but Davis reports that it has a lobe formed at the rim for pouring.¹⁸⁰ Several one-piece pitchers with long, narrow necks remain from the mainland in precious metals.¹⁸¹

¹⁷⁷ Davis, "The Silver Kantharos from Gournia."

¹⁷⁸ Matthäus, *BKMK*, no. 293.

¹⁷⁹ *Ibid.*, no. 299.

¹⁸⁰ Davis, *AGSW*, 102-105, no.13, figs 76, 77.

¹⁸¹ *Ibid.*, nos 29, 65, 91.

Type 30 (**figure 37**) is a small pitcher with a spout extending horizontally from the rim. It has a narrow, splayed foot and the handle is separately-made and attached with rivets. The two surviving examples date to LM IA and are about 180 mm high. No Mycenaean versions exist. Type 40 (**figure 38**) also has a spout extending horizontally at the rim and a separately-made handle, and concave walls. The single vessel extant is quite small at 110 mm high, and dates to LM IIIB.

Type 31 (**figure 39**), has a wide, flat base, walls which curve out somewhat before the shoulder, a narrow neck and out-turned rim with a high spout, and a high strap-handle which loops up from below the rim and comes down to join the shoulder. It is made from two sections which join at the shoulder, and the seam is hidden by a relief-decorated cast collar. Of the two extant, both dated LM IIIA1, one is now only a few fragments and the other has been heavily reconstructed from fragments. The reconstructed vessel is 342 mm high or 412 mm with the handle. This type has not been found on the mainland, although a similar handle from a fragmented Type 22 hydria-type form exists.¹⁸²

Lekanai: BKMK Types 44, 45A1, A2, B1 and B2

These open, flat-based vessels come in several forms, with or without a spout and with one or two handles. Their rim diameters range from 100 to 250 mm. Type 44 (**figure 40**), of which two are extant, has no spout and a single handle. One of these comes from a group dated EM III-MM I, though Hakulin dates it to the Neopalatial.¹⁸³ The other dates to LM IA. Matthäus regards this form as a precursor the later Type 45.

Types 45A1, A2, B1 and B2 (**figure 41**), most of which date to LM IIIA1, usually have two handles, often of the wishbone-type, though they may also be D-shaped loops. Most of the later vessels have spouts. Rims are usually thickened and left plain, though one has relief-decoration on the rim.¹⁸⁴ Lekanai are found in large numbers on the mainland during LH IIIA-B. Some of these have separate, relief-decorated rims and spouts attached to the body with rivets.¹⁸⁵

Ladles: BKMK Types 57B, 57C1 and C2 (figure 42 and figure 43)

There are small number of bronze ladles. The bowl is either hemispherical or with a flat base and out-turned rim, and the handle, which is of the same piece of metal, is either

¹⁸² Matthäus, *BKMK*, no. 258, pl.32.258.

¹⁸³ *Ibid.*, no. 369; Hakulin, *BLMC*, no. 808.

¹⁸⁴ Matthäus, *BKMK*, no. 399.

¹⁸⁵ *Ibid.*, nos 391, 392.

solid with a loop or a strip which loops back to the rim, where it is riveted. They range in height from 70 to 170 mm including the handle, and date between LM IB and LM IIIB. One Mycenaean ladle is extant from LH II and has a solid handle with no loop.¹⁸⁶

Lamps: BKMK Types 58A, B1 and B2 (figure 44 and figure 45)

Lamps have a shallow, rounded- or straight-walled bowl, dropped foot, a long, horizontal handle coming off the rim, and a spout on the rim opposite the handle. The rims are folded out or heavily thickened. The handle of Type 58A is made separately and attached to the rim with rivets. On 58B1 and B2, the handle is a strip of the same piece of metal as the bowl. Some also have a rivet on the handle near the bowl which holds a length of chain. The rim may have relief-decoration. They vary in length from 250 to 400 mm with the handle. In Crete they appear from LM IB to LM IIIA2.

Mycenaean lamps appear between LH I and LH IIIB.

Braziers: BKMK Type 59A (figure 46)

Only two of this type survive in Crete, both dating to LM IB.¹⁸⁷ They are slightly different in form. One is a large, flat pan with a shallow dropped foot and a riveted-on hollow handle. The other has the same large dish and dropped foot, but one side of the dish is folded vertically and the handle is riveted to the back. The hollow handles were probably sockets for wooden rods.¹⁸⁸ They are both decorated with repoussé. Two others have also been found, one on the mainland dated LH II, another at LM IA Thera.¹⁸⁹ Catling and Catling propose that these were used to carry burning fuel to indoor hearths.¹⁹⁰

Sieves: BKMK Type 60 (figure 47)

Three bronze sieves are extant from LM IB Zakros. The only one of which I am aware having been published with description or illustrations is a small, slightly concave dish

¹⁸⁶ Ibid., no.447.

¹⁸⁷ One, from the Unexplored Mansion at Knossos is considered by Catling and Catling to be an heirloom from the LM IB destructions rather than contemporary with the LM II remains at the site. H. W. Catling and E. Catling, "The Bronzes and Metalworking Equipment," in *The Minoan Unexplored Mansion at Knossos*, ed. Mervyn R. Popham, BSA Suppl. 17 (Athens: British School of Archaeology at Athens, 1984), 210.

¹⁸⁸ Ibid., 209.

¹⁸⁹ Matthäus, *BKMK*, nos 468 and 469.

¹⁹⁰ Catling and Catling, "The Bronzes and Metalworking Equipment," 209.

pierced with holes.¹⁹¹ Two Mycenaean sieves are extant, but are now only small fragments of sheet with holes.¹⁹²

§1.2.2. Vessel Parts and Features

Rims (figure 48)

The rims of most of the vessels have been reinforced by some method. This strengthens the vessel by stabilising the walls, preventing them from warping with use. It is rare for a rim on a Minoan vessel not to be reinforced. Many rims types are adaptations of the body material. These are folded out, folded out and in, rolled out over a copper or lead ring, or folded out and down the wall of the vessel (**figure 48, a-d**). Folded-out rims are quite common, found on tripod cauldrons, pans and hydrias. Vessels with rims folded out and in are mostly basins (**figure 11**). Rolled rims are found on a variety of vessels, including pans,¹⁹³ one-handled basins (**figure 24**) and decorated hydrias (**figure 20**). Rims folded out and down are uncommon. I know of only one extant example on a small bowl from LM IB Palaikastro (**figure 16**).

Another type of rim-strengthening involved thickening the rim lightly (**figure 48, e**) or heavily by caulking, often so much so that the section of the rim is T-shaped, and sometimes on an angle (**figure 48, f, g**). Lightly-thickened rims are very common, found on most cups (**figure 27**), bowls (**figure 18**), small pouring vessels, and some lekanai and ladles. The T-section thickened rims are found on most lekanai (**figure 40** and **figure 41**), almost all of the one-handled basins made from a single piece of metal (**figure 23**), small and large pans with a single, vertical handle (**figure 13** and **figure 14**) and the lamps (**figure 45**).

Another rim-strengthening method used was to attach a separately-made rim onto a folded-out rim with rivets (**figure 48, h, i**). These rims have relief-decoration and were made by lost-wax casting.¹⁹⁴ Of the Minoan vessels, only one-handled basins seem to have had this rim type, usually with a matching handle (**figure 25**). Some mainland lekanai also have separate, decorated rims with matching handles and spouts.¹⁹⁵

¹⁹¹ N. Platon, "Anaskaphi Zakrou," *Praktika tis en Athenis Archaologikis Etaireias* (1967): 175, pl. 161b; Matthäus, *BKMK*, no. 471.

¹⁹² Matthäus, *BKMK*, nos 473 and 474.

¹⁹³ Matthäus, *BKMK*, nos 32 and 33.

¹⁹⁴ Catling, *CBMW*, 174; Matthäus, *BKMK*, 329; Evelyn, *Minoan Crafts* 2, 382.

¹⁹⁵ Matthäus, *BKMK*, nos 391, 392, pl. 46.

Handles

Handle types can be divided into two main categories: those which are made from the same piece of metal as the vessel body, and those which are made separately and attached to the body. Those of the same piece may be divided into two sub-categories. The first of these, and the simplest of all the handle types, are strips which extend from the rim and are occasionally riveted back onto the vessel wall (**figure 49, a, b**). These strips would have been hammered out, hence their thin material. These are found on one-handled cups (**figure 26**), ladles (**figure 43**) and lamps, on which they are long and horizontal (**figure 44** and **figure 45**). A more elaborate version of this method is found on the large pans with a single, vertical handle, on which the material is hammered out into a wedge-shaped sheet which is subsequently rolled vertically into a hollow, tapering tube with the edges meeting at the back (**figure 49.c** and **figure 14**).

The other handle type which is of the same metal as the vessel body is more massive than the previous type, and was most likely made by casting as an extended part of the billet and not formed by hammering (**figure 49, d, e**). Such handles are found on the small pans with a single, vertical handle (**figure 13**) and some one-handled basins (**figure 23**).

Separately-made handles, which are more common, can also be divided into two sub-categories: hammered and cast. These are always attached with rivets. Hammered handles (**figure 50**) are easy to identify. The handle itself has a simple section: rectangular or round rod, or strap, which is uniform along its length. The attachment-plates are usually splayed, since the material needed to be thinned to provide a larger and thinner surface for the rivets to go through. This splayed shape is typical of forging. The round or rectangular rod would have been cast straight and the curved profile and attachment-plates subsequently hammered into shape. Strap-handles may have been hammered out from a cast billet. These handles are found on the large cauldrons (**figure 3**), early tripod cauldrons (**figure 4**) and two-handled basins,¹⁹⁶ some hydrias and related forms (lower handle on **figure 19** and probably **figure 21**) and a few miscellaneous vessels (**figure 28**, **figure 33** and **figure 38**). This simple handle-type is far more common on mainland vessels, particularly the various cauldron types,¹⁹⁷ kraters,¹⁹⁸ and many piriform types.¹⁹⁹ These hammered handles are clearly a precursor to the more

¹⁹⁶ Ibid., nos 117, 118.

¹⁹⁷ e.g. *ibid.*, nos 5-9, 17-18.

¹⁹⁸ e.g. *ibid.*, nos 189, 192-198, 205, 207-208.

¹⁹⁹ e.g. *ibid.*, nos 218-219, 221-223, 246.

complex cast handles, since they are relatively simple to make. On Crete, hammered handles are more common on Protopalatial vessels.

Cast separate handles come in a variety of shapes (**figure 51**). These would have been cast in their final form, probably by lost-wax casting. In some cases they may have been hammered slightly to fit them to the vessels. These are identifiable as cast because they have forms which would be very cumbersome to produce by hammering or other hand-techniques. They tend to be massive, with rounded shapes or high relief. In section, the shape is quite variable, not consistent as on hammered handles.

The simplest of the cast handles (**figure 51, a**) is found on Type 6 tripod cauldrons (**figure 5**). The handle is a simple D-shaped loop, rounded in section, and the attachment-plates are rounded and bulbous. Similar handles vary in the shape of the attachment-plates and the handle may be square in section (**figure 51, b-d**). These are found on pans (**figure 8** and **figure 9**) and the lower handles of some hydrias.²⁰⁰ An elaboration on this form is the wishbone-handle (**figure 51, e**), found mostly on lekanai (**figure 41**). The wishbone-handles vary slightly in design of the upper knob. Handles with bull's heads instead of knobs have been found (**figure 51, f**). The wishbone-type is also found on some Mycenaean bronze cups and two silver cups from Enkomi.²⁰¹

Other examples of cast handles are the upper, strap-handles on most Minoan hydrias (**figure 51, g**), the elaborately-decorated handles on many one-handled basins (**figure 51, h**), brazier handles (**figure 51, i**), which are hollow, and the vertical ring-handles on Type 7A, tripod cauldrons (**figure 51, j**). Another type is the spool handles found on the 'Vapheio' cups (**figure 51, k**). Only one of the two extant from Crete is well-published, and it is cast whole.²⁰² Many more spool-handles are found on Mycenaean precious-metal cups. Of these, some are cast and others are fabricated from separate components soldered or riveted together.²⁰³

Legs (figure 52)

Legs are only found on two Minoan vessel types: tripod cauldrons and tripod pans. Leg types were made by two methods, hammering a cast rod or casting the final form. As for handles, forged legs (**figure 52, a**) seem to have been a Protopalatial feature, only seen on Protopalatial Type 5 tripod cauldrons (**figure 4**). The attachment-plates of the later cast legs of Type 6, tripod cauldrons included a bracket which supported the

²⁰⁰ e.g. *ibid.*, no. 238.

²⁰¹ e.g. *ibid.*, nos 349, 350; Davis, *AGSW*, nos 140, 141.

²⁰² Matthäus, *BKMK*, 238-239, no. 357.

²⁰³ e.g. Davis, *AGSW*, nos 39, 63, 70.

curved base of the cauldron body (**figure 52, b, c**). In many cases, the upper part of the attachment-plate was shaped decoratively (**figure 52, d-f**). The legs themselves were usually circular or hexagonal in section. The legs of the round-bodied Type 7A, tripod cauldrons, have a different attachment-plate with less material above the leg and a longer lower section which curved to fit the cauldron (**figure 52, g**). The leg itself curved outwards from the cauldron rather than straight down as on Types 5 and 6. The small legs on the tripod pans (**figure 52, h, i**) were designed similarly to those of Type 6 tripod cauldrons, with a vertical attachment-plate and horizontal bracket attached underneath the pan. Those extant are decoratively shaped.

Spouts (figure 53)

Spouts on extant Minoan vessels are extensions of the material of the vessel body. The simplest of these is on Type 6 tripod cauldrons which have three handles or which have a rim-loop between the two handles (**figure 6**). The spout, which is on the rim opposite the central handle or rim-loop, is a simple adaptation of the out-turned rim. The spout is formed by lowering the rim slightly below the surrounding rim (**figure 53, a**).

However, most spouts extend out from the rim. These are found on various pouring vessels (**figures 27, 36, 37, 38, 39**), some lekanai (**figure 41**) and lamps (**figures 44 and 45**). These spouts may be rounded or square in section and their rims left plain, folded outwards or thickened, particularly on vessels with thickened rims, and the spout is usually horizontal, though some are high (**figure 53, b-g**). A small number of Mycenaean vessels have separately-cast spouts.²⁰⁴

Bases (figure 54)

Most of the vessels have flat or curved bases, but on vessels for which balance may have been an issue, the bases are often deliberately shaped. This is especially the case for hydrias and some other piriform vessels which often have a bulging torus-base or a splayed base (**figure 54, a, b**). A single example of a ring-base exists (**figure 54, c**), though Matthäus says that due to damage, the construction of the base is unclear.²⁰⁵

Some Mycenaean piriform vessels appear to have had a copper plate in the base and in one case also lead, presumably for stability.²⁰⁶ This does not seem to be the case for any extant Minoan piriform vessels.

²⁰⁴ Matthäus, *BKMK*, nos 391, 392 and 477.

²⁰⁵ *Ibid.*, 199, no. 300.

²⁰⁶ *Ibid.*, nos 259, 265-267, 589.

The base-construction of goblets and kylikes is interesting. Unfortunately, the single entire bronze kylix has not been published in sufficient detail to determine its construction.²⁰⁷ However, one of the silver goblets extant (**figure 54, d**) has a copper core in the base.²⁰⁸ Several Mycenaean vessels of this type have copper or lead cores,²⁰⁹ and on others, the entire foot is cast. Matthäus suggests that a bronze item from Postpalatial Chania was such a foot, and Davis believes that the silver goblet from LM II-III A Isopata probably has a cast foot.²¹⁰ Davis suggests that the sheet of those with cores may have been hammered over this core to shape it.²¹¹ An alternative explanation might be that the copper or lead was poured into the foot after it was shaped.

Another common type of base is the dropped foot (**figure 54, e**). All of the one-handled basins have a dropped foot (figures 23, 24, 25), as do most one-handled cups (**figure 26**), several bowls (**figure 17**), some ladles (**figure 42**), the lamps (**figure 44**, **figure 45**) and the braziers (**figure 46**).

Masking-Bands

Some of the piriform vessels in the Minoan-Mycenaean vessel tradition, Type 24, are made from two sections which join at the shoulder and have a relief-decorated band masking the riveted join. These bands are usually cast and are riveted onto the shoulder over the riveted join (**figure 55**). A fair number of Mycenaean examples exist,²¹² but only one Minoan (**figure 21**). The band on this vessel was apparently decorated with chasing rather than cast decoration.²¹³ Although the extant vessels suggest it is a Mycenaean practice, Evelyn says that the presence in Crete of ceramic vessels with shoulder bands suggests that the technique was more widespread than extant metal vessels indicate.²¹⁴

Rivets

Riveted joins are characteristic of vessels in the Minoan-Mycenaean vessel tradition. There are two types of rivets: those with two flush or nearly-flush heads and those with one flush and one large, bulbous head, sometimes referred to as mushroom-head rivets

²⁰⁷ Ibid., 259, no. 368.

²⁰⁸ Davis, *AGSW*, no. 21.

²⁰⁹ e.g. Matthäus, *BKMK*, no. 366; Davis, *AGSW*, no. 85.

²¹⁰ Matthäus, *BKMK*, 259, no. 367; Davis, *AGSW*, 116, no. 22.

²¹¹ Davis, *AGSW*, 112.

²¹² Matthäus, *BKMK*, nos 283-290.

²¹³ Matthäus says that the decoration is engraved, but engraving was probably unknown to the Minoans and chasing is more likely. Ibid., 189, no. 282.

²¹⁴ Evelyn, *Minoan Crafts* 2, 382.

(figure 56). Flush-head rivets are more common, used to join sections on the large cauldrons, multi-piece tripod cauldrons and the hydrias and other multi-piece piriform vessels (figures 3, 19, 20, 21, 22, 33). They are also used to join rims, handles, legs and other attachments to most vessel types. Mushroom-head rivets seem to be reserved for conspicuous positions, with the mushroom head on the more visible side and the flush head on the other side. The rims of hydrias and the insides of tripod cauldrons and lekanai are some examples. For this reason, they may have served more of an aesthetic than a functional purpose, though they are still only used where a rivet is required. Evelyn suggests that they may have helped to spread stresses during use of the vessels and might have improved waterproofing.²¹⁵ Davis says that the mushroom-head rivets seem to be a Minoan innovation, since they occur less frequently on Mycenaean vessels.²¹⁶

Decoration

I will not go into detail on the decorative techniques used on Minoan vessels since the aim of this study is only to understand the manner in which the vessels were made. Techniques found on some vessels are repoussé, seen on some hydrias (figure 20) and precious-metal cups,²¹⁷ chasing on a small number of vessels (figure 21), inlay, found on a copper “Vapheio” cup said to be from Crete (figure 30), but more commonly seen on Mycenaean vessels,²¹⁸ soldered-on overlays on some precious-metal vessels (figure 57), and lastly, relief-decorated cast components such as rims and handles, which have been discussed above in the relevant sections.

Miscellaneous: Repair Patches, Rim-Loops and Protomes

Repair patches, which are thin pieces of sheet fixed over holes or cracks in bronze vessels with fine rivets, were commonly used on bronze vessels (e.g. figures 12 and 33). Rim loops, found on some Type 6 tripod cauldrons (figure 6), are a narrow strip of sheet rolled into a loop at one end and riveted just under the rim so that the loop rises above it. Since these loops appear in the same position as small handles on some similar Type 6 tripod cauldrons opposite a spout on the rim, the loop was probably intended to be used as a grip when pouring out the contents. Lastly, a single Minoan vessel, a large-

²¹⁵ Ibid., 384.

²¹⁶ Davis, *AGSW*, 329, 339.

²¹⁷ e.g. *ibid.*, no. 19.

²¹⁸ Ibid., nos 83, 109, 119, 130. Inlaid precious-metal vessels are often thought to be of Minoan manufacture.

mouthed piriform vessel, has a bird-like protome attached to the rim (figure 22). A better example can be seen on a Mycenaean bronze tankard.²¹⁹ The protome on the Minoan vessel may be more functional than decorative, perhaps intended to be used as a grip.²²⁰ It was probably made by lost-wax casting.

§1.2.3. Metals and Alloys

The alloying of copper with arsenic and later tin to create bronze was a major step in metallurgy. Pure copper is a difficult material to work with for several reasons. It has a relatively high melting temperature, 1089°C (cf. 1063° for gold and 960.5° for silver), and tends to develop gaseous inclusions when molten, resulting in porous material upon solidification.²²¹ This porosity causes problems because these inclusions are weaknesses which create cracks during hammering. Copper's tendency to react with oxygen while molten also results in copper oxide inclusions which cause the material to become brittle. However, pure copper without inclusions is quite soft, and while it is easy to hammer, tools made with it tend to become blunt quickly and vessels to dent easily. The addition of arsenic or tin improves the material substantially. Both reduce the melting temperature (approximately 950°C for tin bronze, depending on the percentage of tin), making it easier to cast. They also act as antioxidants, reducing or eliminating the porosity of the cast material and copper oxide inclusions. The inclusion of arsenic or tin improves the hardness, creating a material which is more difficult to hammer, but much more durable. Tin bronzes can be hardened to a greater extent than arsenic bronzes, although Papadimitriou says that an arsenic percentage of 6 or 7% creates an alloy which is able to be work-hardened without cracking, to an extent almost equivalent to tin bronzes.²²² Both tin and arsenic change the colour of the metal. Arsenic lightens the colour and, depending upon the percentage, tin changes the colour to yellow and gold at higher percentages.

Arsenic bronze, however, probably has limited benefits for hammered-vessel manufacture. Although the workability of the metal is improved, arsenic is not stable in the alloy, and dissipates with repeated heating, leaving a brittle structure. Since

²¹⁹ Matthäus, *BKMK*, no. 360.

²²⁰ Popham, Catling, and Catling, "Sellopoulo," 236, no. 28.

²²¹ J. R. Brown, ed. *Foseco Non-Ferrous Foundryman's Handbook* (Oxford: Butterworth-Heinemann, 2000), 232.

²²² G. Papadimitriou, "The Technological Evolution of Copper Alloys in the Aegean during the Prehistoric Period," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008), 278.

hammered sheet requires repeated annealing, arsenic bronze may not be ideal.²²³ Tin bronzes, however, are very suitable for vessel-making. According to Papadimitriou, as well as being able to be work-hardened well, they have good cold-workability and the tin is stable in the alloy, allowing unlimited annealing.²²⁴ The attributes of tin bronzes change substantially with different percentages of tin. Up to 8%, the material has good cold-workability as long as it does not cool too slowly after casting. Slow cooling reduces the presence of the brittle, intermetallic δ -phase which is characteristic of tin bronzes. Above 8%, the alloy has reduced cold-workability and requires repeated annealing due to the greater concentration of δ -phase. Above 12%, the material cannot normally be cold-worked without cracking, but must be hot-worked above 600°C, since δ -phase is not present in the material at these temperatures.²²⁵ However, experiments conducted on tin bronzes by Papadimitriou showed that a 10.8% tin-bronze could be cold-worked if, after casting, the alloy is annealed and quenched in cold water, since this freezes the microstructure in the malleable α -phase.²²⁶ A 14.8% tin-bronze could also be made workable, though the process is slightly more complex. The cast metal is annealed, quenched in cold water, worked to 15% deformation then annealed and quenched again. The resulting material has similar cold-workability to a medium-tin-content bronze.

During the EBA and MBA in the Aegean, arsenical coppers and arsenical bronzes dominated metalworking.²²⁷ During the MBA, the range of alloys used increased, and there are signs of selective alloying: for example, the use of lead to improve the castability of copper for cast figurines. Tin bronzes began to appear, but arsenical bronzes were still common. In the LBA, tin bronzes dominated, and in Crete during the Neopalatial period, there are clear signs of a sophisticated understanding of the qualities of different alloys. Analyses by Evely and Stos show that weapons were generally 10% tin, tools 5-9% and vessels 7-12%.²²⁸ In Knossos during the Monopalatial period, vessels remained at 7-12%, swords were 9-14%, knives 4-9%, spearheads 1-2% and 10-12%, double axes and some chisels were 10-14%, while smaller items which required

²²³ Ibid., 280.

²²⁴ Ibid., 282.

²²⁵ Ibid., 286.

²²⁶ G. Papadimitriou, "Simulation Study of Ancient Bronzes: Their Mechanical and Metalworking Properties," in *Archaeometry Issues in Greek Prehistory and Antiquity*, ed. Yannis Bassiakos, Eleni Aloupi, and Georgeos Fakorellis (Athens: Hellenic Society of Archaeometry: Society of Messenian Archaeological Studies, 2001), 718-719.

²²⁷ Mangou and Ioannou, "CBAC."; Papadimitriou, "Technological Evolution of Copper Alloys," 277, 280.

²²⁸ Evely and Stos, "Aspects of Late Minoan Metallurgy at Knossos," 276.

high deformation such as rivets and staples were of copper. The benefits of selective alloying were well understood.

Although Evelyn and Stos's analyses indicate vessel alloys of 7-12% tin during the Neopalatial and Monopalatial periods, published data provides a different picture. I am aware of analyses of only 40 vessel bodies, and such a small sample is not a reasonable representation of the entire corpus of Minoan vessels. However, the data does indicate that a broad range of alloys was used. An abbreviated list of this data is shown in Table 2 and Table 3 (full details, including references, are provided in Appendix Two).

Table 2. Alloy Compositions of Vessel Bodies

No.	Description	Period	Cu	Sn	As	Pb
1	tripod cauldron body	LM	98.212	0	trace	trace
2	two-handled basin	MM IIIB	100	0		
3	two-handled basin	LM IB	100	0		
4	large cauldron	LM IB	100	0		
5	tripod cauldron body	MM II		0.16	2.2	0.69
6	tripod cauldron body	MM II		0.17	1.9	0.68
7	vase base	MM II		0.543	1.7	0.981
8	vase	MM II		0.83	1.14	1.14
9	hydria body	LBA	82.73	0.19	0.44	0.08
10	pot body	LBA	90.75	0.2	0.8	0.04
11	pitcher body	LBA	66.78	0.21	0.21	0.09
12	laver body	LBA	90.44	0.39	0.1	0.04
13	laver body	LBA	82.67	0.91	0.33	0
14	rim	LM II		1	1	
15	rim	LM II		1		
16	hydria body	LM IIIA1	81.6	2.37	0.24	0.07
17	rim	LM II		4		
18	hydria handle	LM IIIA1	64.68	4.31	0.03	0.09
19	body	LM II		5		
20	body	LM II		5.5		
21	body	LM II		5.5		
22	bowl	LM IB	93.4	6.4	0.3	<0.2
23	laver body	LM IA	87.16	6.72	0.13	
24	laver body	LBA	69.46	6.78	0.08	0
25	scale pan	LM IIIA1		8.5		
26	bowl	LM IB	90.9	8.6	<0.2	<0.2
27	laver body	LM IIIA1	82.72	8.76	0.23	0.04
28	deco sheet	LM II		9		
29	pan	LM IIIA1		9.1		1.1
30	lamp w/ skillet handle	LM IIIA1		9.4		
31	body	LM II		9.5		
32	body	LM II		9.5		
33	pan	LM IIIA1	82.93	10.34	0.31	0.04
34	deco sheet	LM II		10.5		
35	rim	LM II		11		
36	body	LM II		12		
37	rim	LM II		12.5	1	1
38	oinochoe body	LM IIIA1		15		
39	body	LM II		15-17.5		

No.	Description	Period	Cu	Sn	As	Pb
40	lamp w/ skillet handle	LM IIIA1		>20	1	1

Sources: H. W. Catling and R. E. Jones, "Sellopoulo Tomb 4: Some Analyses," *BSA* 71 (1976); H. W. Catling and R. E. Jones, "Analyses of Copper and Bronze Artefacts from the Unexplored Mansion, Knossos," *Archaeometry* 19 (1977); Matthäus, *BKMK*; C. Éluère, "Appendice III. Étude en laboratoire de quelques objets métalliques du Quartier Mu," in *Artisans minoens: Les Maisons-Ateliers du quartier Mu*, ed. J.-C. Poursat, *ÉtCrét* 32 (Athens: École Française d'Athènes, 1996); Mangou and Ioannou, "Chemical Composition of Prehistoric Greek Copper-Based Artefacts"; J. S. Soles and Z. A. Stos-Gale, "The Metal Finds and their Geological Sources," in *Mochlos IC*, ed. J. S. Soles and C. Davaras (Philadelphia: INSTAP Academic Press, 2004); Hakulin, *BLMC*. For full references see Appendix Two.

Table 3. Alloy Compositions of Handles and Miscellaneous Attachments

No.	Description	Period	Cu	Sn	As	Pb
44	laver handle	LBA	88.89	0.19	0.74	0.16
45	hydria handle	LBA	89.64	0.2	0.4	0.28
46	handle	LBA	91.93	0.2	0.87	1.08
47	handle	LBA	89.14	0.2	1	3.52
48	pitcher handle	LBA	84.35	0.22	0.31	1.68
49	handle	MM II		0.44	0.57	0.2
50	laver handle	LBA	87.17	0.63	0.24	0.09
51	pot handle	LBA	91.49	0.79	0.72	0.9
52	handle	LM II		1		
53	handle	MM II		1.3	1.7	0.9
54	tripod cauldron leg	LM IIIA1		5.8		
55	handle	LM II		6		
56	handle	MM II		8.9	0.68	0.213
57	laver handle	LM IIIA1	81.1	9.7	0.11	0
58	handle	LM II		12.5		
59	oinochoe handle	LM IIIA1		16		
60	handle	LM II		20-22.5		
62	hydria protome	LM IIIA1		5.5		
63	oinochoe masking-band	LM IIIA1		20		

Source: Data from Catling and Jones, "Sellopoulo Tomb 4: Some Analyses."; Catling and Jones, "Copper and Bronze Artefacts."; Éluère, "objets métalliques"; Mangou and Ioannou, "Chemical Composition of Prehistoric Greek Copper-Based Artefacts." For full references see Appendix Two.

Five of the analysed vessel bodies are MM, four of which are arsenic bronzes containing between 1.14 and 2.2% arsenic and only trace amounts of tin, fitting neatly into the pattern of the development of arsenic and tin bronzes described above. Of the remaining 35 vessels, which date to LM, 22.9% contain less than 1% tin, which may be regarded as an undeliberate alloy and very close to pure copper. Those containing 1-7% tin, which are the easily-hammered alloys, make up 31.4% of the total. Alloys above 8% and less than 12% tin, which are more difficult to cold work, also make up 34.3%, and alloys above 12%, high-tin bronzes which require special treatment to cold work,

make up 11.4% of the total. These figures indicate that a broad range of alloys was used for vessel bodies.

Also of interest is that, of LM vessel handles which have been tested for lead content, several have significantly more lead in them than most of the vessel bodies tested: between 0.16 and 1.68% against usual quantities in the vessels of nil to less than 0.2%. Lead significantly improves the casting qualities of bronze, but is detrimental for hammering at concentrations above 0.2-0.3%.²²⁹ Lead's extremely low melting temperature (327.4°C) makes it very unstable during annealing, causing the material to become prone to cracking with hammering. The fact that these handles contain a substantial amount of lead indicates that they were cast in their final form.

The presence of larger quantities of lead in some of the vessel bodies indicates that, assuming the analyses are accurate, they were almost certainly cast in their final form or, if they were hammered at all, it must have been very little. Three of these vessels, nos 29, 37 and 40, also have tin concentrations which would make them difficult to hammer, another factor indicating that they may have been cast in their final form. However, no. 29, a pan, was badly damaged and has been heavily reconstructed, so the analysis may not be reliable. No. 37, described only as a rim, may be a separate, cast rim such as those on Type 32E one-handed basins. No. 40, a lamp, is quite likely to have been cast. However, the high concentrations of lead in the four MM II vessels from Malia Quartier Mu (nos 5-8) are difficult to account for, especially the two tripod cauldrons, which would have required extensive hammering.

Since the range of alloys used to make vessels was so broad, it is difficult to determine what factors would have been involved in the choices of alloys. The figures indicate that Minoan smiths managed to overcome problems associated with working copper and the higher tin bronzes, so perhaps creating the ideal working material was not always the primary concern. Certainly, the availability of resources would have affected the choices, especially the availability of tin, which was imported to Crete from very far afield and so must have been extremely valuable. Another important factor must have been colour. The yellow to golden hue of tin bronzes must have made these alloys desirable. Soles suggests that two simple bronze bowls from Mochlos, with 6.4 and 8.6% tin respectively (nos 22 and 26), must have been alloyed for colour, since the strength of such forms was not important.²³⁰ He proposes that such colour-choices may

²²⁹ Papadimitriou, "Technological Evolution of Copper Alloys," 287.

²³⁰ Soles, "Conclusions," 141.

have been for ideological purposes. This is another factor which may account for alloy choices for vessel manufacture.

The matter of the precious-metal alloys used in Crete can hardly be covered sufficiently, given the lack of extant vessels. Of these fourteen-odd vessels, one is gold, though it apparently has a dull colour which indicates that it is alloyed.²³¹ The rest are silver, only one of which has been analysed, as far as I am aware, and contains a trace amount of copper.²³²

§1.3. Purposes of the Vessels

Matthäus suggests a broad framework for determining functions for some of the vessels.²³³ Cups and some bowls were probably for drinking, hydrias and other pouring vessels were clearly for transferring liquid, cauldrons, tripod cauldrons, basins and pans were probably for heating during food preparation, and others were specialised forms – sieves, lamps and braziers. He suggests that some may have been intended for cult practices: the one-handled basins, kylikes, some pouring vessels, bowls and the braziers. Beyond these broad categorisations, it is very difficult to draw any concrete conclusions.

Metal vessels must have been extremely valuable, given not only the high value of the material itself, which was probably exacerbated in Crete by the lack of local ore sources, but also because of the amount of labour which would have been required to manufacture the vessels. Knappett suggests that metal vessels must have been restricted in their distribution.²³⁴

To this end we might consider the social role of metal vessels. The possibility that they were used in drinking ceremonies has been suggested by several scholars.²³⁵ In particular, the role of metal vessels in feasts may indicate their true use and meaning within Minoan culture. Evidence suggests that patron-role feasting and ceremonial consumption were integral to Mycenaean and Minoan societies: establishing and maintaining community relationships, expressing ideological constructions, and

²³¹ Davis, *AGSW*, 109, no. 19.

²³² Catling and Jones, "ST4," 22.

²³³ Matthäus, *BKMK*, 343-344.

²³⁴ Knappett, "The Material Culture," 125.

²³⁵ Sherratt and Taylor, "Metal Vessels in Bronze Age Europe and the Context of Vulchetrun," 106-107; J. C. Wright, "A Survey of Evidence for Feasting in Mycenaean Society," *Hesperia* 73, no. 2, Special Issue: The Mycenaean Feast (2004), 137-145; J. S. Soles, *Mochlos IIA: Period IV: The Mycenaean Settlement and Cemetery*, Prehistory Monographs 23 (INSTAP Academic Press, 2008), 143, 155.

reinforcing alliances while simultaneously reinforcing social stratification.²³⁶ One way in which the latter is enacted is by conspicuous consumption with a hierarchy of feasting equipment. The patrons and elite within the group, using metal vessels, underscore their superiority over community members (and perhaps also guests) who use ceramic vessels, which reflect further layers of hierarchy.²³⁷ Minoan vessel forms which Wright suggests for feasting include tripod and other cauldrons, 'lekanai, lamps, basins, bowls, cups, pitchers, pans and hydrias.²³⁸ Related to this use of metal vessels for reinforcing power and status are competitive, conspicuous burial practices in which valuable grave-goods signify the status and wealth of the deceased.²³⁹ Wright suggests that the presence of metal vessels in burials reflects the status of the individual by reference to their ability to sponsor feasts.²⁴⁰

A further important role of metal vessels must have been in gift exchange with both local and international elites. Gift exchange not only reinforces alliances but also strengthens power-roles between elites through the association of gift-value with expendability of resources. The value of a gift reflects the wealth and associated power of an elite. The presence of Minoan imports in the shaft graves at Mycenae could indicate such gift exchange. Further afield, in Eighteenth Dynasty tomb wall-paintings at Thebes, people called the 'Keftiu', who are usually interpreted as Minoans,²⁴¹ bring gifts, including many precious-metal vessels, for the Pharaoh.²⁴² The use of metal vessels for such important political strategies implies the high value attributed to them.

§1.4. Characteristics of Minoan Vessel Forms

A feature which is very characteristic of Minoan vessels is that they are almost exclusively open forms or, if closed, they are made from open sections riveted together (see for example figure 19). Tall, narrow vessels are also virtually absent. This

²³⁶ E. Borgna, "Aegean Feasting: A Minoan Perspective," *Hesperia* 73, no. 2, Special Issue: The Mycenaean Feast (2004); Knappett, "The Material Culture," 125.

²³⁷ Knappett, "The Material Culture," 125.

²³⁸ Wright, "Feasting in Mycenaean Society," 146.

²³⁹ K. Shelton, "Mainland Greece," in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2011), 141; C. Mee, "Death and Burial," in *The Oxford Handbook of the Bronze Age Aegean*, ed. Eric H. Cline (Oxford: Oxford University Press, 2011), 285.

²⁴⁰ Wright, "Feasting in Mycenaean Society," 147.

²⁴¹ Betancourt, "Minoan Trade," 219.

²⁴² S. Wachsmann, *Aegeans in the Theban Tombs*, *Orientalia Lovaniensia Analecta* 20 (Leuven: Peeters, 1987), 49-50, 55-74; D. Panagiotopoulos, "Keftiu in Context: Theban Tomb Paintings as a Historical Source," *OJA* 20 (2001); Younger and Rehak, "The Material Culture," 157. Note, however, that Wachsmann says that many of the vessels depicted in the tomb-paintings are hybrids, often of Egyptian forms.

contrasts strongly with vessels of other cultures producing metal vessels in this part of the world during the same period and even earlier. Although open vessels were also produced elsewhere, many vessels in other cultures are closed and of a single piece of metal or are tall and narrow. Examples include the silver spouted bottles and various beakers from the Early Dynastic IIIA Royal Tombs at Ur (**figure 58**),²⁴³ gold pitchers from EBA Central Anatolia (**figure 59**),²⁴⁴ vases from Troy IIg levels (**figure 60**),²⁴⁵ and the many Hes vases, flasks and pitchers from contemporary Egypt and earlier (**figure 61**). Laffineur believes that, for Mycenaean vessels, this is a result of them having been formed over a core which needed to be removed after the vessel's shaping.²⁴⁶ I do not believe that this is the case (for discussion of the core-formed-vessel technique, see §3.4). This contrast represents an important technological difference in the approach to vessel-making used in Crete. Tall, narrow vessels and closed vessels can be worked only from the outside by raising the vessel over a stake and, for narrow-mouthed, closed forms, the stake needs to be curved in order to reach into the vessel. The stake almost certainly would have to be made from metal in order to withstand the heavy hammer blows required to make such shapes (for full discussion of raising and stakes required to make specific forms, see §2.1.4). Open forms, however, are made almost exclusively by working the vessel from the inside. The metal is carefully forged from one side or beaten over a hemispherical hollow to achieve the open shape (see §2.1.4). Some open shapes also require hammering from the outside over a stake; however, the Minoan forms of this type require only a straight wooden stake.

It is also significant that there are many more large vessel types in the Minoan-Mycenaean corpus than in those of other contemporary cultures. The largest of the Minoan vessels, the type 1 cauldrons which are up to 1250 mm in diameter, are the largest of any known vessels from the period. The next largest Minoan vessels are some of the hydrias, which are up to 600 mm high, and tripod cauldrons which are up to 610 mm in diameter. Two-handled basins were up to 650 mm in diameter. Medium-sized vessels such as smaller versions of the above types as well as pans, one-handled basins and some pitchers range around 400 mm at their largest dimension.

²⁴³ c. 2550-2400 BC.

²⁴⁴ c. 2700-2000 BC.

²⁴⁵ c. 2350-2100 BC.

²⁴⁶ R. Laffineur, "Craftsmen and Craftsmanship in Mycenaean Greece: For a Multimedia Approach," in *POLITEIA*, ed. Robert Laffineur and Wolf-Dietrich Niemeier, Aegaeum 12 (Liège: Université de Liège, 1995), 194.

By contrast, of the 500 Egyptian bronze vessels catalogued in Radwan's *Die Kupfer- und Bronzegefäße Ägyptens: Von den Anfängen bis zum Beginn der Spätzeit*,²⁴⁷ the average large vessel is around 300 mm at its largest dimension. A small number are larger, up to 400 mm, and one or two come close to 600 mm. Overall, the average vessel is 200 mm or less at its largest dimension. Similarly, of the 1600 or so Mesopotamian bronze and precious metal vessels catalogued by Müller-Karpe in *Metallgefäße im Iraq I*,²⁴⁸ most of the larger vessels are in the vicinity of 400 mm at their largest dimensions and a very small number are around 500 mm.

After the Bronze Age, the production of large vessels became more common. The gigantic cauldrons produced in Cyprus after the Bronze Age seem to be the largest after Minoan forms. It may be significant that Cypriot metalworking has been regarded as having been heavily influenced by the Minoan-Mycenaean tradition because of the Mycenaean presence in Cyprus at the end of the Bronze Age.

In this chapter, we have reviewed the development of Minoan vessels, their types, features, materials, potential purposes and meaning, and noted their characteristics within the broader framework of Bronze Age vessel manufacture. We are now in a better position to look at the methods used to manufacture the vessels. Before Minoan vessel-making technology is examined, however, the technology and techniques required to make any hammered vessels are illustrated and discussed.

²⁴⁷ A. Radwan, *Die Kupfer- und Bronzegefäße Ägyptens: Von den Anfängen bis zum Beginn der Spätzeit*, *Prähistorische Bronzefunde. Abteilung II; Bd.2* (München: C.H. Beck, 1983).

²⁴⁸ M. Müller-Karpe, *Metallgefäße im Iraq I*, *Prähistorische Bronzefunde. Abteilung II; Bd.14* (München: C.H. Beck, 1993).

Modern Hammered-Vessel Manufacture

To reconstruct how Minoan vessels were made, the process which is used to make hammered vessels must be examined. In this chapter, the modern process is described as well as the equipment required. This outline provides a means for understanding how vessels are made and what metalsmithing techniques are required in any period. By establishing this, we will be in a position to identify the evidence for these processes in Minoan material.

§2.1. The Modern Vessel-Making Process

There are fundamental tasks required to make hammered vessels. The order of these is as follows:

1. Sourcing the metal
2. Creating the blank from which the vessel can be made
3. Annealing
4. Shaping
5. Finishing
6. Further working

The manner in which each of these tasks is undertaken in a modern metalsmithing workshop is illustrated in this section. The exact techniques and types of equipment can vary from one workshop to another and from one vessel to another according to available resources, personal preferences and the vessel being created. The tasks themselves, however, do not change. The modern process illustrated does not list every variation in technique and equipment, but those which are typical.

§2.1.1. Acquiring the Metal

The form that the metal takes at the beginning of the process affects how a vessel is made. The techniques used to transform a thick billet into a vessel are quite different from those used to transform sheet. The types of metals which are used to create hammered vessels today include gold, silver, copper, copper alloys such as brass and

gilding metal, and aluminium. Mild steel and even stainless steel are also known to be hammered into vessels, though the latter requires unusual treatment. Usually, for manufacturing hammered hollowware, a smith purchases sheet no finer than 0.9 mm and no thicker than 2 mm. This usually comes in a square or rectangular shape, although pre-cut discs are available in some metals.

§2.1.2. Making the Billet from which the Vessel is Hammered

Raising, the main hammering process for vessel manufacture, is most suitable for radially symmetrical forms, and for such vessels it is usual to start with a disc.²⁴⁹ In some cases an ellipse may be used to create an oblong vessel, and other shapes such as squares are also possible, though less common. Because Minoan vessels are all radially symmetrical, these other possibilities are not covered here. If the final form is to have an extra feature on its rim such as a spout or a handle which is of the same piece of metal (as on several of the Minoan vessels) then an allowance for this is included on the edge of the disc. The smith marks out a circle on the sheet using a compass and cuts out the disc with shears or, more usually, with a piercing saw, supporting the sheet on a bench pin attached to a jeweller's bench (figure 62).

§2.1.3. Annealing

Because these vessels are formed by hammering, annealing plays a large role in their construction. Hammer blows force the grains of the metal to elongate in the direction of deformation, causing the material to become brittle and less malleable, which inhibits further deformation and creates the potential for cracks to form. This is referred to as work-hardening. In order for work to continue, the grains must be made to recrystallise so that they become even in size and with random orientations, releasing stresses in the material to allow further deformation. This is achieved by annealing the metal, heating it to a temperature and for long enough to cause the crystals to form small-grained, stress-free structures.²⁵⁰ If the metal is heated for too long, however, the grains become too large, which inhibits deformation.²⁵¹ It is usually beneficial after annealing to

²⁴⁹ Hammered vessels which are not radially symmetrical in their final form are usually initially formed to be so and are subsequently manipulated into their final shape, and as such are usually hammered from a disc.

²⁵⁰ E. Brepohl, *The Theory and Practice of Goldsmithing*, trans. Charles Lewton-Brain (Portland: Brynmorgen Press, 2001), 156, 164.

²⁵¹ *Ibid.*, 165.

quench the metal in order to halt the recrystallization process at the correct moment, retaining the ideal grain structure.

During the forming process, the metal requires frequent annealing as it becomes work-hardened. It often requires annealing before hammering begins if previous manufacturing processes have hardened it, as is usually the case with rolled sheet. In a modern metalsmithing workshop a gas torch is used to anneal the metal, usually with natural gas or liquid propane gas. The metal lies on a bed of heat resistant material. Ideally, this does not draw heat away from the metal, and for this pumice or charcoal are commonly used. Other possible materials include refractory bricks or hebel (aerated concrete). When the metal has reached annealing temperature, the flame is removed and the disc is either left to air-cool or quenched by picking it up with metal tongs and placing it under a running tap or in a bucket of water. Other less common modern annealing methods include placing the metal in a temperature-controlled kiln or a bath of molten salt.

For some metals, the material requires pickling after annealing to remove oxide layers which form during heating. If the oxide is hammered into the metal, it can cause cracks. Copper and alloys containing some copper, such as sterling silver, are usually pickled. This is achieved by submerging the metal in a bath of diluted sulphuric acid, referred to as pickle. The metal is subsequently rinsed. Alternatively, the oxide may be removed with the use of abrasives, but this is uncommon, since there will inevitably be loss of material on the surface. Over the course of making a vessel, which may require annealing twenty times or more, the use of abrasives can amount to significant material loss.

§2.1.4. Shaping

Hammering processes create the hollow form of the vessel. Three main hammering processes are used: sinking, raising and forging. Another process, crimping, may also be used in the initial stages as an alternative to sinking. Sinking, spiral-forging and raising deform the metal into the hollow form: sinking and spiral-forging by causing the metal to become concave, thereby stretching and thinning the material (**figure 63**), and raising by gradually bringing the walls up towards or beyond vertical (**figure 64**). Forging is used to a lesser extent to complement sinking and raising by moving, stretching and/or compressing material where required. The specific combinations of

sinking, raising and forging are different for each vessel and vary according to personal choice. Between rounds of hammering the work must be annealed.

The shaping of a vessel is carried out in the following manner. The outer band of the flat disc, which will form the walls of the final vessel, must be brought up from horizontal while the centre of the disc, which forms the base, is left virtually untouched. The initial stages of this are achieved with one of three methods: by crimping, which creates a shallow, open dish with a flat base and straight walls, or by either sinking or spiral-forging, both of which make the disc concave. Subsequently, the walls are raised up further to vertical or beyond in the case of closed forms. The main forming process is raising, but this is not usually carried out on a flat disc, which is why one of the above three processes is used initially. Alternatively, an open form without high, vertical walls may be formed by sinking or spiral-forging alone. At various stages, forging or further sinking may be used to alter the shape. The different forming processes will now be discussed in greater detail.

Forging

Forging is any hammering process where the metal is worked by hammering metal on an anvil or stake. It is distinct from raising and sinking in which the metal is hammered on air, with the supporting tool underneath, an anvil or stake, acting simply as a means of supporting the metal surrounding, but not at, the point at which the hammer strikes. During forging, the metal is sandwiched between the hammer and the anvil. If the metal conforms to the shape of the anvil or stake, this forces the material surrounding the point of impact to move outward (**figure 65, centre**). Further forging moves the metal along the direction of hammering (**figure 65, bottom**). If the material has irregularities in its profile, these can be eliminated by forging them to conform to the anvil or stake underneath (**figure 66**). Traditional forging hammers have one cross-peen face and one slightly convex face, which are used in combination for various forging techniques (**figure 67**).

Forging is the most common metalsmithing technique. It is used for both general material movement and consolidation, or for fine, accurate shaping. It may be performed on cold metal (cold forging) or on hot metal (hot forging). The latter is particularly useful for moving material quickly. There are some specialised forging techniques which may be used to produce hammered vessels and are known by other names: crimping, planishing and caulking. Each of these is described later in this chapter. The technique mentioned above, spiral-forging, can be used to create a

concave form. The disc is placed on the flat top of an anvil and, using a convex hammer-face, the disc is struck, beginning at the centre and moving out towards the rim in a spiral fashion or concentric circles, always overlapping each hammer blow (**figure 68**). The disc is turned after each hammer blow so that the point which is being struck is always on the flat anvil-face. This causes the material on the underside to stretch as the material moves out towards the rim, resulting in a concave form. Spiral-forging is only suitable for thick material, since the material becomes quite thin, and it cannot be used to create deep hollow forms. Rather it is only useful for creating a shallow dish.

Modern forging hammers are usually steel, since the weight of the hammer head plays an important part in moving the material. The surface on which the metal is forged may be a steel anvil or stake, though in some cases it may be performed on wood, which causes less damage to the metal's surface. In recent years plastic (delrin) stakes have become available, which also reduce surface damage.

*Sinking*²⁵²

Sinking is hammering metal sheet over one or a series of hollows using a hammer with a round, convex face (**figure 69**). As with spiral-forging, this causes the sheet to become concave by stretching the material, also causing it to become thinner (**figure 63**). A hollow with a diameter which is large relative to the sheet can be used for general sinking of large areas, and smaller diameters are useful for both overall and localised sinking (**figure 70**). The depth of the hollow is not important so long as the stretching of the sheet is not impeded by the bottom of the hollow. The goal is not necessarily to make the metal match the profile of the hollow. It is the action of the edges of the hollow, which support the sheet surrounding the point at which the hammer strikes, which is important. Sinking is hammering the metal on air, and the diameter of the hollow affects the diameter of the area which is being stretched and how far it is stretched. The process is also affected by the arc on the face of the hammer. Usually, the arc should correspond with that of the hollow. If the face is too small relative to the hollow, the resulting hammer blow rebounds off the sheet, creating only minor stretching and, usually, undesired deformation of the surrounding material. If it is too large, the hammer face presses the sheet onto the surface surrounding the hollow, creating unwanted deformation and causing the material to stretch only slightly into the hollow. Sinking is carried out by overlapping hammer blows in a spiral fashion,

²⁵² Some metalsmiths refer to this process as blocking or hollowing and, confusingly, the term sinking is sometimes used to refer to the spiral-forging process described above.

beginning either from the rim or the centre, so that a part or the whole of the sheet is made concave by the overlapping of many smaller concave areas (figure 68).

During the vessel-making process, sinking is used at the beginning to transform the flat disc into a concave form and at later stages localised sinking may be used to refine the vessel's profile. Modern hammers used for sinking have convex faces and are often heavy, which helps to stretch the material (figure 71). Hammers may be made from steel, plastics such as nylon or delrin, or wood. Sinking hollows are usually carved in wood, the top of a tree stump being the most convenient, since the weight of the stump provides stability. Other methods include sinking into a sandbag or pitch.

Crimping

Crimping, which can be used as an alternative to sinking in the initial pre-raising stages, utilises a combination of sinking and forging on a specialised stake (figure 72).

Crimping can only be performed on sheet. A sector of the outer band of the disc, which will form the walls, is held across the stake and sunk into the stake's groove with a cross-peen hammer. This is repeated around the disc until the entire outer band is fluted. Subsequently, the crimped segments are forged against a stake with a cross-peen hammer. Hammer blows are applied perpendicularly across the flutes from the centre outwards, flattening them. The resulting shape is a shallow, flat-based dish with everted walls. This process may be performed several times to bring the walls up further and is interspersed with annealing. Crimping can cause alternating vertical bands of thick and thin material in the vessel's wall, which may cause vertical cracks during later stages if care is not taken. Modern hammers used for crimping are steel cross-peen hammers, and the stake, which is secured in a vice bolted to a bench or stump, is wooden.

Raising

The raising process is used to shape the concave form by hammering it over a stake, working the wall upwards (figure 73). The metal is held against the stake at approximately 30° and turned clockwise or anti-clockwise while being hammered parallel to the rim in a spiral or concentric-circle fashion, the hammer strokes overlapping. It is commonly worked from near the centre and out towards the rim.²⁵³ The metal is not hammered on the stake surface, but rather a few millimetres above, where the metal rests on the stake, so that the hammer blows push the metal over the

²⁵³ A technique called Dutch raising involves raising from rim to centre.

stake at the rate of a couple of square centimetres per hammer blow (**figure 74**).

Raising works by flattening an arc of the wall into a chord, repeating that on the adjacent arc and so on, thereby reducing the circumference of the vessel (**figure 64**).²⁵⁴ The stake has a flattened upper surface so as to support the material on either side of this arc. The metal is being hammered on air as for sinking rather than on the working surface as for forging.

These two actions cause the walls to slowly move up and in towards the centre, and should occur evenly around walls. They are also inclined to stretch vertically, so that they become longer. It usually takes many rounds of raising before a vessel is complete; the larger and more complex the vessel, the more rounds required. The vessel is annealed after each round. In order to create different vessel profiles, a round of raising may begin at different points on the profile so that the wall forms different angles and curves (see below).

The movement that the material undergoes may be visualised as the movement of the walls of a clay vessel on a potter's wheel being brought up to vertical. It is brought in evenly from all sides and must be carried out in stages to avoid uneven deformation. Because raising compresses material, reducing a large rim circumference to one far smaller, the fabric thickens, especially at the rim, where the greatest amount of fabric has been compressed.

Raising is the main process by which vertically-walled vessels are formed. It can also be used to create closed forms by bringing the walls in beyond vertical. Raising closed vessels usually requires specially-shaped stakes. In **figure 74**, the type of stake illustrated is straight, the simplest type, which can generally only be used to create open forms, since the stake must always be able to reach through the opening of the vessel. Such stakes can be used to bring the edge of the rim in over the wall of the vessel slightly, but not extensively.

To create closed forms, the stake must be a more complex shape. To make a closed vessel such as the form illustrated in **figure 76**, several stages are required involving two or more stakes. These stages are illustrated in **figure 77**. Beginning with the flat disc, the centre is left flat for the base, and the surrounding material raised upwards from point 1 on the profile, which marks the edge of the base. This would be carried out with a simple, straight stake such as that illustrated in **figure 74**. The material is raised upwards over several rounds until the wall reaches an angle approximating the

²⁵⁴ H. Maryon, "Metalworking in the Ancient World," *AJA* 53, no. 2 (1949): 99.

first dotted line above the flat line. The next stage begins from point 2, the goal being to raise the material to vertical. The straight stake is still used for this stage over several rounds. Once the wall is vertical, the material needs to be brought inwards, starting from point 3. From now on, as the rim becomes narrower it begins to become difficult to raise on the straight stake, since it is too large to fit it through the opening. During the last stages, the material needs to be raised inwards to form the neck from point 4, narrowing it substantially at point 5. It is for these stages that a stake such as that shown in **figure 78** is required. The neck can easily be worked over such a stake, as can the lower wall for any further shaping required there, since the end of the stake is shaped to suit the desired vessel profile, but is narrow enough to fit through the small opening.

An alternative method requires a stake called a snarling iron (**figure 79**). The vessel is first raised into a cylinder or similar shape. The part of the wall which is to have a bulge is held firmly over the stake with the hemispherical face of the stake touching the inside of the wall. The shaft of the stake is then struck with a hammer, causing a recoil in the stake which makes the stake-face strike the inside of the vessel wall, pushing it outwards.

Modern raising hammers usually have cross-peen or wedge-shaped faces, although it is possible to raise, somewhat less efficiently, with a flat or convex hammer face. The hammer is usually made from steel, though hardwood and nylon are also suitable, and horn hammers were common until recent times (**figure 80**). Simple, straight stakes are commonly carved from wood (**figure 81**). These are very versatile since they are easy to shape and can be adapted to suit the vessel being made. Similar stakes are also made from steel. Complex stakes for making closed vessels such as that illustrated in **figure 78** or the snarling iron in **figure 79** can only be made from metal, although, in recent times, sturdy plastics such as delrin may be used. An essential requirement for a raising stake is that it must not move during hammering. Because of the narrowness and curves required on these stakes, timber is not suitable, since its springiness would cause it to bounce during hammering and, more than likely, to snap under the repeated, heavy hammer blows. Steel stakes come in a large range of shapes (**figure 82**).

A common method for holding stakes is to fix them in a vice bolted to a heavy work-bench or a wooden stump (**figure 81**). This prevents the stake from bouncing during use. Some sets of stakes consist of a range of steel stakes with tapered shafts which sit in a purpose-made stake-holder fixed to a solid surface (**figure 83**). These provide the

versatility required for the many different profiles which may be required in a workshop.

§2.1.5. Finishing

After the vessel has been formed with hammering processes, it must usually be refined and the profile made consistent around its circumference. At this stage, the profile is still uneven with irregular variations in its curves and the sheet itself is dented and marked by hammer blows. Also, the surface of the metal is scuffed, scratched and dull. Finishing is a two-stage process. The first involves material deformation with planishing to create the final profile and the second involves cutting the metal's surface to create a polish.

Planishing

With planishing, the hammer blows from raising are smoothed and the final profile is created with localised deformation over the vessel's walls. Planishing involves gently forging the entire surface of the vessel over a stake which conforms to the profile of the vessel or of the part which is being planished. It is usually performed on the outer surface, but the inside may also be planished if it is accessible. Planishing achieves three ends. The first is general smoothing of dents and ripples in the material, the second localised adjustment of the profile and the third hardening of the material.

To smooth out the material, the work is held firmly over an undented steel stake such as those in figure 82. With a planishing hammer, the smith applies overlapping blows, turning the vessel so that the point being struck is always sitting on the face of the stake (figure 84). A planishing hammer has two faces: one completely flat and the other slightly convex (figure 85). The faces must be undented, since any irregularities are transferred to the vessel's surface. The point at which the hammer strikes must be precisely the point at which the vessel's wall touches the stake, as it is the forging action which smooths out the material. This is carried out over the entire surface and repeated several times. The material hardens more with each successive round. Planishing, especially with a steel hammer on a steel stake, stretches the material, making the form larger and the material thinner. It may also be performed with a rawhide or other soft-material mallet for more general smoothing without excessive stretching, though the finish is not as smooth and the material not well hardened. To prevent excessive stretching, the vessel is not usually annealed once planishing has begun.

The tendency of planishing to cause material to stretch is exploited to achieve localised adjustments in the profile. Once the walls are smoothed out, it is easy to see small irregularities in the profile such as low spots and high spots. Low spots can be made to pop out and conform to the profile of the surrounding material by careful localised planishing and high spots may be gently tapped down on air (**figure 86**). A template of the vessel's profile can be used to check where these irregularities occur, or they can be detected by touch and observation of reflections on the surface. Planishing creates a distinctive faceted surface (**figure 87**), and the underside becomes dimpled.

Polishing

In order to create a polish on the metal's surface, diffusion of light waves from the surface are reduced by removing scratches and scuff marks and making the surface as smooth as possible. This can be achieved by cutting back the surface with abrasive materials, burnishing, or a combination of the two. Burnishing is rubbing the surface very hard with a tool made from a hard material such as steel or haematite. This presses down the material around any scratches, making the surface smooth and reflective. Since no material is removed in the process, none is lost, as it is with abrasives. However, it is not common to burnish vessels in modern workshops because it is more time consuming and labour intensive than using abrasives. The three usual methods for polishing are filing, emerying and buffing (**figure 88**). Each stage involves cutting back the surface with progressively finer cuts, resulting in a polished surface.

First, the facets left from planishing are filed off. Files of varying grades can be used. Coarse files cut quickly but leave deep scratches which must be removed with a finer grade of file. A file which is very fine takes longer to cut and has a tendency to become clogged, but there is less risk of removing too much material, which makes the walls thin. The vessel is held steady during filing so that the file strokes are even and chances of the file slipping and causing deep scratches is reduced. The usual method for holding it steady is by pressing it against a fixed object such as a bench or against the smith's own body.

Emerying removes the scratches left from filing. This is achieved by applying different grades of emery paper to the surface. Initially, the whole surface is cut back with a coarse grade to remove the file scratches. The emery dust is then washed off the surface and the resulting smaller scratches removed with a finer grade of emery. This is performed several times with reducing emery grades. A typical sequence of grades used is 400, 600, 1200, and 2000.

The emery paper can be held in the hand and rubbed over the surface, but there is a tendency for the surface to become rippled because pressure is not applied evenly. Often the paper is attached to a hard surface which can be easily manipulated by hand over the surface. A piece of hardwood or metal bar with similar dimensions to a file are ideal. Often, water is used as a lubricant.

A high polish is achieved with a polishing compound, which cuts back the fine scratches left from the final emery used. Polishing compounds are fine-grained abrasives suspended in a waxy substance. Usually, one or two grades are used: tripoli and rouge respectively. The polish can be applied by hand with a piece of leather, sometimes glued to a strip of timber, or with a calico or flannelette polishing mop attached to a motor. Excess polish must be removed from the surface, especially if a second, finer polish is to be used. Methylated spirits or hot water with detergent are commonly used. Finally, the vessel can be rubbed with a polish-impregnated felt cloth.

§2.1.6. Further Working

Further processes which may be carried out on the hammered form vary according to available technology and aesthetic preferences. These processes generally fit into three categories: further shaping, further construction and decoration. The options available to the modern smith for further working are numerous. A small number of these are listed as examples.

For further shaping, the hammered form may be further manipulated to alter its shape. Usually such processes would be carried out before the finishing processes, since the polished finish might be damaged. The rim may be caulked. Raising usually leaves the rim uneven and ragged. Caulking is a type of forging whereby the upper surface of the rim is hammered back down into the wall to flatten and thicken it (**figure 89**). This is usually carried out concurrently with raising and finished after the shaping is complete. The form can be altered by chasing, manipulating the material with steel punches. A spout can be forged out from the wall, or the wall might be otherwise altered to change its profile, perhaps to create an asymmetrical form. Alternatively, a spout can be hammered out from material on the rim allocated for the purpose when the initial disc was cut out. The rim may also be altered by cutting it with a piercing saw.

For further construction, the hammered form may be joined with other elements. Often, the hammered form is only a part of the whole vessel. Attachments are often added: a spout and handle to a teapot for example, or feet and handles to a tray. Two or

more hammered forms may also be joined together. On modern vessels, attachments and other hammered forms are often joined to the vessel body by hard soldering, though they may also be joined by welding or with cold-joining mechanisms such as rivets, bolts and screws. In some cases, parts may be joined with adhesives such as epoxy resin. The methods for joining sections vary according not only to design, but also the metal being used. Solder is frequently used for gold, silver, and copper alloys, but metals such as aluminium must be joined by other means.

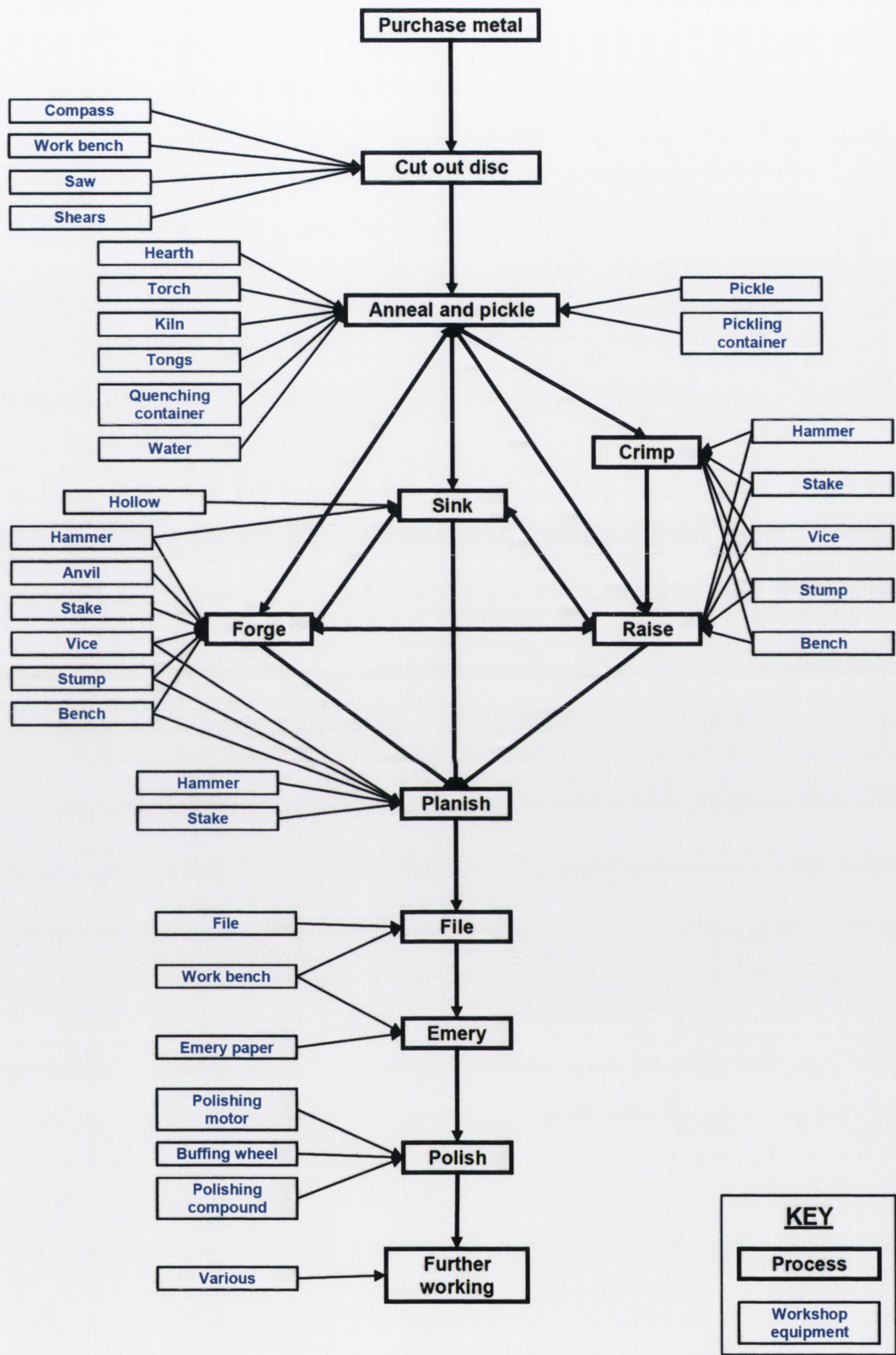
Finally, the hammered form may be physically or chemically altered to decorate the surface, or it may have other elements attached to it for decorative effect. The means for decorating metal forms today are numerous. Figurative decoration may be applied with engraving, repoussé, chasing, enamelling, etching and inlay. Decorative elements can be attached to the vessel with hot or cold joining methods. The properties of particular metals may also be exploited to colour the surface with chemical patination or anodising.

The modern vessel-making process described above can be broken down into sets of specific tasks and their associated methods:

acquiring the metal	purchase metal sheet
creating the initial form	cut out disc
annealing	anneal and pickle
shaping	sink or crimp, anneal and pickle, raise, anneal and pickle, repeat raising, sinking and forging as required interspersed with annealing and pickling
finishing	planish, file, emery, polish
further working	various

This process can be expressed as a flow chart illustrating the order of the tasks (**Chart 1**). This illustrates the interaction between the different tasks and the resources required for each one.

Chart 1. The Modern Metal Vessel Manufacturing Process



§2.2. Reconstructing the Minoan Process

In attempting to reconstruct the Minoan process, we must make some assumptions about the smith's choice of techniques and methods. There are many variables in any craft process according to personal choice, available resources and customs. It is difficult to anticipate some such factors in a prehistoric craft since little evidence of these is left in the archaeological record. Personal choice has been mentioned previously in relation to modern metalworking processes. For Minoan smiths, it must be kept in mind that an individual may have chosen one technique or piece of equipment over another for no reason other than that the individual happens to enjoy carrying out that particular technique or using that particular tool. The matter of available resources will be covered in later chapters which examine the archaeological evidence. How social customs or traditions may have affected the process is probably impossible to determine. We know next to nothing about how social, political and economic systems may have affected a Minoan artisan's choice of tools or techniques.²⁵⁵

Metal must have been a valuable material and therefore wastage of material would have been minimised. Knappett points out that since Crete did not have its own sources of metal, metal vessels must have been highly valued.²⁵⁶ It is important to bear this in mind, because if a smith has no concern for conserving materials, the variety of processes which might be used is different.

Minoan smiths probably avoided unnecessarily prolonging the process by using excessively laborious techniques. This assumption is made tentatively, however, because we can not assume that modern standards of efficiency in production were relevant for Minoan smiths. We might assume today that it is in the interests of a Minoan smith to carry out a task as quickly and efficiently as possible in order to maximise production. However, we cannot know what a Minoan smith's priorities may have been, or even whether two different smiths from different periods or different regions during the same period may have had the same priorities. It is possible, for example, that some complex ritual aspects of the craft required particular processes to be undertaken in a way which we might regard as inefficient. Nonetheless, we will presume that some degree of conservation of materials and labour was exercised.

²⁵⁵ C. Costin, "Craft Specialisation: Issues in Defining, Documenting and Explaining the Organization of Production," *Archaeological Method and Theory* 3 (1991): 2.

²⁵⁶ Knappett, "The Material Culture," 125.

In this chapter, we have identified the essential tasks required to make hammered metal vessels today and are in a position to ask how a Minoan smith might have made a metal vessel. The tasks would have been the same, but the means would have been different. In Chapter Three, we will evaluate some theories which have been proposed in the past about how vessels may have been made in prehistory.

Evaluation of Theories on Prehistoric Vessel Manufacture

Several theories about the manner in which metal vessels were made in prehistory have developed. In some cases, these ideas seem to have been developed with little understanding of metalsmithing processes and the nature of metals undergoing deformation. In this chapter, these ideas are evaluated with reference to metalsmithing practice and historical and archaeological corroborative evidence.

§3.1. Hammering from a Cast Disc-Billet

Catling and Evelyn both suggest that Cypriot and Minoan vessels were hammered from disc-shaped billets, and that for vessels on which the handle is of the same piece of metal as the body, the billet was cast with a provision at the edge of the billet.²⁵⁷

Catling cites a thick, shallow bronze dish from Enkomi as an unfinished example (figure 90).²⁵⁸ Brogan suggests that two bronze discs from LM IA Mochlos may have been intended for vessel production.²⁵⁹ Two moulds for disc-billets from MM III Malia may have been used for making such billets.²⁶⁰

The manner in which such a billet was transformed into a vessel is rarely discussed. It seems to be a common assumption that, during prehistory, vessels were hammered out from pre-fabricated sheet.²⁶¹ This requires the thick, cast billet to be forged out into sheet and subsequently raised into a vessel. Since modern vessel-making is carried out in this manner from pre-fabricated sheet, it seems an obvious conclusion that it has always been done this way. However, the dominance of this technique today is probably due to the existence of rolled sheet, which has only been available since the

²⁵⁷ Catling, *CBMW*, 137, 147-8, 162; Popham, Catling, and Catling, "Sellopoulo," 231-238, 242, 247-251; Evelyn, *Minoan Crafts* 2, 382.

²⁵⁸ Catling, *CBMW*, 147, 287, fig. 17.4, pl. 19b.

²⁵⁹ T. M. Brogan, "Metalworking at Mochlos before the Appearance of the Artisans' Quarters," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008), 163.

²⁶⁰ C. Renfrew, *The Emergence of Civilisation: the Cyclades and the Aegean in the Third Millennium B.C.* (London: Methuen, 1972), 317.

²⁶¹ Branigan, *AM*, 89; Johnson, "An Experiment in Ancient Egyptian Silver Vessel Manufacture.," C. Rolley, *Greek Bronzes* (London: Sotheby, 1986), 27; Evelyn, *Minoan Crafts* 2, 382.

development of the rolling mill during the 16th or 17th century AD.²⁶² For constructing chalices, the 16th century writer Theophilus describes forging a billet until it can be bent by hand before sinking and raising the vessel sections.²⁶³ Such a thickness would vary depending on the metal being used, but would probably be no more than 2.5 mm, perhaps closer to 1.5 mm. For Minoan vessels, this method is most likely for smaller forms such as small cups, bowls, ladles and so on.

For producing large vessels such as hydrias, cauldrons and pans, forging out the billet into sheet and then hammering the vessel into shape would be extremely laborious. To carry out both steps is a waste of time and labour unless it is absolutely necessary. It is possible both to stretch the billet into thin sheet and to create the hollow form at the same time. Two of the hammering processes described in Chapter Two, sinking and spiral-forging (§2.1.4), can be used to do this and are suitable for working thick material.

A method for transforming a thick billet into a vessel was described by Cellini and has been demonstrated by Fröhlich.²⁶⁴ In Cellini's description, the cast billet is forged to increase its diameter and reduce its thickness and is then made concave by spiral-forging. Once the centre is concave and the form is the shape of a brimmed hat, the walls are raised upwards (**figure 91**). The spiral-forging method is appropriate for thick material (over 2 mm), and is still used by modern metalsmiths. Since spiral-forging is not suitable for thin material, Cellini can not have been advising to forge the billet into sheet before beginning the shaping. Sinking achieves a similar result to spiral-forging. Neither method is suitable for thin sheet since they both stretch the material.

The Cypriot bronze dish mentioned above which Catling describes as an incomplete vessel has a shape typical of this method (**figure 90**). As the middle of the disc is forged or sunk, the rim gradually turns upwards as the diameter of the outer wall increases (see, for example, these initial hammering stages illustrated in **figure 63**). The rim remains very thick and close to the original diameter of the billet unless it is deliberately forged thinner.

²⁶² W. Alexander and A. Street, *Metals in the Service of Man*, 3rd ed. (Harmondsworth: Penguin Books, 1954), 83-4; H. Newman, *An Illustrated Dictionary of Silverware: 2,373 Entries Relating to British and North American Wares, Decorative Techniques and Styles, and Leading Designers and Makers, Principally from c.1500 to the Present* (London: Thames and Hudson, 1987).

²⁶³ Theophilus, *On Divers Arts*, trans. John G. Hawthorne and Cyril Stanley Smith (New York: Dover, 1979), 99-104.

²⁶⁴ B. Cellini, *The Treatises of Benvenuto Cellini on Goldsmithing and Sculpture*, trans. C. R. Ashbee (New York: Dover Publications, 1967), 85-86; M. Fröhlich and R. Fröhlich, *Abhandlungen über die Goldschmiedekunst und die Bildhauerei* (Basel: Gewerbemuseum Basel, 1974), 80-81, 131, nn. 80, 81.

Middle sections of large hydrias consist of a vessel with no base. Evelyn suggests two possibilities for the construction of these. One is that they were hammered out from ring-shaped billets and the other is that they were hammered up as normal vessels with bases and the base removed prior to connection of the sections.²⁶⁵ There is no evidence for the production of ring-shaped billets, and it may be difficult to stretch out such a billet since at some point hammering would need to be carried out from the inside of the ring in order to stretch its diameter, and accessing the inside of the ring with the hammer would be quite difficult. The second suggestion of the bases being removed subsequent to hammering is much more feasible. Another similar method would be to cut a hole in the base as the shape is nearing completion. This hole is smaller than the diameter of the final hole required and is subsequently stretched to the desired diameter (**figure 92**). The material at the base must be quite thick to begin with, as the material at the rim of the hole will become very thin. The benefit of this method over that of hammering out the entire base and then removing it is that less material will be removed, which means that the initial billet doesn't need to be as large. It also requires less labour, since there is no need to hammer out material which will only be removed. The choice as to which of these two methods a smith uses probably would depend upon the training and personal preferences of the smith, not to mention the amount of material available.

§3.2. Cast Vessels

There are a small number of vessels in the Minoan-Mycenaean vessel tradition which are thought to have been cast.²⁶⁶ Minoan vessels which are thought to have been cast are a 'Vapheio' cup from MM III Mochlos (**figure 93**) and some lamps.²⁶⁷ These rare occurrences of cast vessels are very curious indeed, since there is no evidence that the technique for making thin-walled castings such as these was known in Crete during the Bronze Age. Casting of vessels was apparently uncommon in prehistory. It is difficult to find confirmed examples of cast vessels. One Mesopotamian Early Dynastic III²⁶⁸ copper alloy cup and an Egyptian Eighteenth Dynasty²⁶⁹ bronze dish appear to have been produced by casting (**figures 94, 95 and 96**). Both of these, as well as the Minoan

²⁶⁵ Evelyn, *Minoan Crafts* 2, 382.

²⁶⁶ Matthäus, *BKMK*, 326-327.

²⁶⁷ *Ibid.*, no. 357; Evelyn, *Minoan Crafts* 2, 382.

²⁶⁸ c. 2600-2350.

²⁶⁹ c. 1479-1425.

cup, are open forms which are somewhat less complex to cast than a closed form. Casting of both open and closed vessels became more common in Greece during the fourth century BC.²⁷⁰

The moulds used for casting by the Minoans were open and bivalve stone moulds, open ceramic moulds and ceramic lost-wax moulds (for further discussion of moulds see §4.2.2). Of these, only bivalve and lost-wax moulds can be used to cast vessels. Of the extant Minoan bivalve moulds, none shows the sophistication required for vessel casting. Vessel casting in bivalve moulds was common during the Roman period, and many of the moulds remain (**figure 97**).²⁷¹ These consist of two sections carefully carved so that the smaller, inner section sits in the upper lip of the outer section, leaving a narrow gap between the two for the molten metal to fill. Minoan bivalve moulds are relatively simple and were used for casting solid forms rather than hollow, thin-walled pieces. A similar problem exists for lost-wax moulds. There is little evidence in the Aegean of hollow casting by lost-wax casting other than the remains of an unusual mould for a hollow hand found at Phaistos. This is discussed by Laviosa who concludes that it must have been a one-off experiment (see §4.2.2).²⁷² Apart from this handful of vessels, there are no other extant metal objects which show the use of such techniques. If it were common practice, we should certainly expect to see more examples of the method. I can only conclude that, if vessels were cast, it is most likely that they were made by lost-wax casting and were anomalies within the tradition. For some reason the technique was not widely adopted, even for producing other metal items. Metallographic analyses of the vessels in question would help to resolve this issue.

§3.3. Hammering a Cast Proto-Vessel

Matthäus proposes that some vessels were made by casting a proto-vessel, smaller and thicker than the final form, which was hammered out to become larger and thinner. He suggests this method for a mainland lekane from Dendra which appears to have cast

²⁷⁰ D. K. Hill, "The Technique of Greek Metal Vases and its Bearing on Vase Forms in Metal and Pottery," *AJA* 51, no. 3 (1947): 250.

²⁷¹ D. Brown, "Bronze and Pewter," in *Roman Crafts*, ed. Donald Strong and David Brown (London: Gerald Duckworth & Co., 1976), 33-34.

²⁷² C. Laviosa, "Una Forma Minoica per Fusione a Cera Perduta," *Annuario* 45-46 (1967/68).

relief-decoration on the rim (**figure 98**).²⁷³ The same thick-walled, shallow bowl mentioned above which Catling describes as the beginnings of a billet being transformed into a vessel is cited by Matthäus as an example of a cast proto-vessel yet to be hammered into shape.²⁷⁴ That this object is typical of a billet which has been hammered for one or two rounds has already been discussed above. This hammering of a cast proto-vessel is thought to have been carried out during later historical periods. Pernot claims that the gigantic Vix crater was made in this way, by casting a small, thick-walled, vessel which was then hammered out (**figure 99**).²⁷⁵

My main objection to the method is that it would be extremely difficult to carry out on any but the simplest of shapes. The unfinished billet/proto-vessel from Enkomi (**figure 90**) might not present many problems since its shape is so close to that of a billet, but to forge out a more complex shape such as a lekane from a rough-cast, hollow shape would be rather difficult. The main problem would be having the correct tools. For this method to work, the material would have to be meticulously planished to thin and stretch it, and this would have to be repeated over and over again. It would require a number of metal stakes which fit perfectly into the various different profiles of the vessel, since it would be impossible to planish the material from the inside anywhere other than the bottom centre due to the difficulty of accessing the inner walls with a hammer. With modern equipment the technique may be possible, but since, as was discussed previously (§1.4), Minoan vessel forms indicate that raising was used only minimally, Minoan smiths are very unlikely to have had the knowledge of metal stakes required to use such a method.

For the Vix crater, even with more advanced Iron Age technology, this method seems unlikely. By Pernot's calculations, the cast proto-vessel would have had a wall between 5 and 6 mm thick, a diameter averaging 600 mm and a weight of 60 kg. To planish such thick material on such a vast scale down as thin as 1 mm would be a massive undertaking. It would be extremely unwieldy to handle, to manipulate a 60 kg piece over the faces of stakes for the careful hammering required for planishing, and it would certainly require an assistant to handle the vessel. Planishing requires the smith

²⁷³ Matthäus, *BKMK*, 266, 326, no. 399, pl. 47.399. Catling describes the decoration as "traced". It is unclear whether the term is meant generally or technically. When used technically, it often refers to chasing or engraving. Catling, *CBMW*, 172, no. 22.

²⁷⁴ Matthäus, *BKMK*, 327; H. Matthäus, *Metallgefäße und Gefäßuntersätze der Bronzezeit, der geometrischen und archaischen Periode auf Cypern, mit einem Anhang der bronzezeitlichen Schwertfunde auf Cypern*, *Prähistorische Bronzefunde. Abteilung II; Bd.8* (München: C.H. Beck, 1985), 80, no. 142, pl. 7.142.

²⁷⁵ M. Pernot, "Étude technique de quelques objets en bronze," in *La tombe princière de Vix*, ed. Claude Rolley (Paris: 2003), 266-267.

to be able to feel when the surface being worked is on the correct part of the stake's working face. On material 5 or 6 mm thick, this would be extremely difficult, especially if an assistant is handling the vessel. It is far more likely that the Vix crater was hammered from a flat billet with the method described by Cellini.

An alternative to this method is that a flat billet for a vessel such as the lekane from Dendra (figure 98) was cast with the relief decoration on the outer circumference of the billet. Catling suggests this method for a one-handled basin from Sellopoulo (figure 100).²⁷⁶ Although this is more plausible, there are still some objections to this method. When a disc is hammered, even when the rim is avoided, it is still pulled out of shape by the movement of the rest of the material, and tends to reduce in diameter. If there is cast decoration on the rim, it is likely to be deformed by this movement. However, since the relief decoration on these vessels appears to have been cast, this must be the explanation. Minoan smiths must have known a technique to prevent warping of the rim. Otherwise, an alternative explanation for decorating the rim after the vessel had been hammered must be sought. In the absence of proper analyses it is impossible to draw conclusions in this regard.

§3.4. Hammering over a Core

Another technique which has been proposed for vessel manufacture is hammering sheet over a pre-shaped core which conforms to the inside of the metal vessel.²⁷⁷ Laffineur proposes that some of the gold vessels from Mainland Greece were made by this method with stone cores.²⁷⁸ There are several reasons why it is doubtful that this technique would have been used for making vessels. The main objection is that it is actually not physically possible to manipulate metal by this method three-dimensionally and on the scale required for vessel-making, although creating relief decoration on flat gold sheet by die-forming is certainly possible and was used by Minoan and Mycenaean smiths.²⁷⁹

The idea of this method being used for vessel manufacture may have developed from the observation that many pieces of gold jewellery from Classical Greece have three-dimensional gold-sheet forms, usually human or animal heads, which have a bronze

²⁷⁶ Popham, Catling, and Catling, "Sellopoulo," 236, no. 27, fig. 22.27; Matthäus, *BKMK*, no. 312.

²⁷⁷ B. Segall, *Katalog der Goldschmiede Arbeiten, Benaki Museum* (Athens: Benaki Museum, 1938), 11; Hill, "Technique of Greek Metal Vases," 248.

²⁷⁸ Laffineur, "Craftsmen and Craftsmanship," 194-196.

²⁷⁹ *Ibid.*, 192-193.

core within. Several scholars have said that such pieces were formed by working the gold sheet over the core.²⁸⁰ However, I have been unable to find any example of a specific object which has been shown by scientific analyses to have been made in this way. It is more usual for such gold elements to be formed from two open halves made by die-forming and these are subsequently soldered together.²⁸¹ They were often afterwards filled with some substance such as plaster, wax or resin for strength.²⁸² It is possible that they were soldered together over bronze cores for similar reasons. In any case, one may concede that it might be possible to force unalloyed gold sheet to conform to tiny cores such as these, but it would not be feasible to work it in such a way on the larger scale required for vessels. Maryon has discussed this issue:

....from the view of the practical craftsman it is not mechanically possible to contract the rim of a bowl....by giving it a series of blows near its edge in order to make it fit a wooden pattern held within it. A skilled metal-worker would admit that the effect of a blow near the edge....would be to drive in the metal at that spot. But it would bulge out just as much somewhere else. Indeed, the effect of continued blows near the edge would be not to contract the rim, but actually to expand it.²⁸³

As was illustrated in Chapter Two (§2.1.4), the stake over which a vessel is raised is not the same shape as the vessel being made, it is a simple form which is designed to allow the circumference of the metal form to contract by providing a surface over which a small arc of the circumference is flattened into a chord (figure 75). It is not possible to raise sheet over a perfectly-fitting core. If the sheet were hammered at any point over such a working surface, the material on either side of the hammer blow would be forced to bow outwards and the material under the hammer would be planished thinner, thus stretching, which is why, as Maryon states, the rim, or indeed whichever part of the vessel is being hammered, would expand (figure 101).

Another problem raised by Maryon is that if a closed form were made with such a method, the core would be locked inside it. The vessel would need to be annealed many times, and this would be impossible with a core inside it. Core material such as clay, stone or bronze would draw heat away from the metal, making it very difficult to achieve the correct temperature consistently around the vessel. A wooden core would be destroyed during annealing, long before the vessel had reached its final form.

²⁸⁰ H. Hoffman and P. F. Davidson, *Greek Gold: Jewelry from the Age of Alexander*, ed. Axel von Saldern (1965), 28-29; J. M. Ogden, *Jewellery of the Ancient World* (London: Rizzoli, 1982), 39.

²⁸¹ e.g. D. Williams and J. Ogden, *Greek Gold: Jewellery of the Classical World* (London: British Museum Press, 1994), nos 103, 111, 132, 161 amongst others.

²⁸² *Ibid.*, 19.

²⁸³ Maryon, "Metalworking in the Ancient World," 99.

Maryon says that the silver lion heads from Ur have been described as having been made in this fashion (**figure 102**).²⁸⁴ However, he explains that these would have been formed by hammering a hollow vessel form in the usual way and subsequently chasing the ears and facial structure.²⁸⁵ This technique would have been used to make the lion's- and bull's-head rhytons from Shaft Grave IV at Mycenae.²⁸⁶ Any core used would not have conformed to the facial details, but would have been a roughly-shaped piece of wood covered in a thick layer of bitumen, resin or wax into which the metal could be chased (**figure 103**). With this method, between chasing rounds, the form can be gently heated to soften the bitumen or wax so that the core can be removed and the metal annealed.

A gold bull's head on a lyre from Ur has been described as having been hammered over a wooden matrix, since a wooden form is still within the gold (**figure 104**).²⁸⁷ The fact that the bull's head was reconstructed because the original wooden core had badly disintegrated is apparently disregarded.²⁸⁸ If we assume that the reconstruction is accurate, the presence of a wooden core in the final form does not mean that the head was formed by hammering the sheet over that core. The fact that the gold does not completely encase the core strengthens this argument all the more, indicating that the core was added after forming. The sheet would first have been hammered into the hollow vessel-shape required but without the finer features on the muzzle and eyebrows. The wooden core, carefully carved to fit into the metal form, and with the relief features carved into it, would have been inserted into the gold form and fixed in place. At this stage the gold sheet, which is quite thin, may have been burnished into the features on the muzzle and eyebrows carved into the wooden core if these features had not already been chased into the surface over bitumen.

Laffineur argues that some Mycenaean gold vessels with relief decoration were hammered over cores,²⁸⁹ saying that it would not have been possible to create this decoration by repoussé because of the difficulty of raising the material from the inside,

²⁸⁴ Penn B17064.

²⁸⁵ Maryon, "Metalworking in the Ancient World," 99-100. Hansen quotes a personal communication with Fleming who says that the lion heads were probably cast but that analysis is not possible due to the corrosion of the silver. D. P. Hansen, "Art of the Royal Tombs of Ur: A Brief Interpretation," in *Treasures from the Royal Tombs of Ur* ed. Richard L. Zettler and Lee Horne (Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology, 1998), 51 and note 14.

²⁸⁶ Davis, *AGSW*, 179-183, no. 62, figs 146, 147 and 187-190, no. 64, figs 151, 152. NM 273 and NM 412. The bull's ears are cast and riveted in place.

²⁸⁷ Penn B17694; C. L. Woolley, *The Development of Sumerian Art* (Connecticut: Greenwood Press, 1981), 76, pl. 34.

²⁸⁸ Hansen, "Art of the Royal Tombs of Ur: A Brief Interpretation," 54.

²⁸⁹ Davis, *AGSW*, nos 103, 104 and 116. NM 1758, 1759 and 116.

especially on a convex surface. The explanation, he claims, is that they were formed over stone cores with the relief decoration carved into their surfaces.²⁹⁰ Such cores would have allowed for multiple, identical vessels to be made. Laffineur does acknowledge that no two identical vessels have been discovered, nor any cores. Triester disagrees with Laffineur and concludes from examinations of the vessels in question that the relief decoration appears to have been produced with repoussé.²⁹¹ It is strange that Laffineur decides that the relief decoration could not have been formed by repoussé on convex surfaces since it has been used on such forms continuously throughout history and continues to be used today. The technique is straightforward. The entire vessel is completely formed by hammering first. Where the relief is to be applied, a rounded punch can be held against the inner surface and the general area pushed out using hand pressure, pressing the material out further for the areas of higher relief. At this point no specific detail is required, so a raised bump is produced. The vessel is then filled with a bituminous compound or a similar material and all of the detail is brought out by pushing material back in from the front. Details are subsequently added by chasing the surface.

One of Laffineur's arguments for hammering over a core being used to form Mycenaean vessels is that many of the forms are open or constructed from open sections, which allows for removal of the core on completion. As was discussed previously in Chapter One (§1.4), this predominance of open forms is a result of the vessels being worked mainly from the inside with minimal raising. Laffineur's concern with his core theory is that if a semi-closed vessel such as the gold octopus cup (**figure 105**) were being made, the core would be locked in place. His explanation, however, is that the core would have been removed after the lower half of the vessel was complete, and the rim brought in afterwards. An issue which Laffineur does not seem to consider is that the core would be locked in place by the relief decoration itself. If the walls of a vessel were somehow hammered over such a core, the relief protruding from the surface of the core would now be locked within the relief on the vessel's wall, even on an open vessel (**figure 106**).

²⁹⁰ Laffineur, "Craftsmen and Craftsmanship," 194-196.

²⁹¹ M. Y. Treister, *Hammering Techniques in Greek and Roman Jewellery and Toreutics* (Leiden: Brill, 2001), 7.

Of the methods for vessel-production proposed by others and discussed here, the casting of disc-billets and disc-billets with provisions on the rim for handles and other rim protrusions is the only method for which there is corroborative evidence in the form of contemporary metallurgical equipment and known precedents. It is also the most plausible method from a metalsmithing point of view. Due to the evidence discussed, I believe that this was the method used to make Minoan hammered vessels. Although it is possible that vessels were occasionally cast complete, this seems not to have been the preferred method.

Minoan Metallurgical Equipment and the Vessel-Making Process

In Chapter Two the basic processes required to make a hammered vessel were outlined (Chart 1):

7. Sourcing the metal
8. Creating the blank from which the vessel can be made
9. Annealing
10. Shaping
11. Finishing
12. Further working

Chapter Four evaluated some theories about how vessels were formed in prehistory. The most feasible of these is hammering from disc-billets. This chapter will investigate what metallurgical equipment was available to Minoan smiths and how this technology relates to vessel production. Artefacts listed in this chapter which come from a metallurgical context are marked with †.

§4.1. Sourcing the Metal

It is generally acknowledged that Crete had insufficient copper ore to meet the requirements for bronze smithing during the LBA.²⁹² Some scholars do make a case for the mining of copper on Crete. A particularly compelling argument comes from Tzachili, who believes that Crete's potential as a source of ores during the Bronze Age is dismissed because of preconceptions about the feasibility of ore extraction which are based on modern conditions and in the modern metals market.²⁹³ The debate about Cretan copper ores is outside the scope of the present study. There are sources of argentiferous galena on Crete, but no evidence of it having been exploited during the Bronze Age,²⁹⁴ and there are no sources of gold on Crete.

²⁹² Evelyn, *Minoan Crafts* 2, 335; Hakulin, *BLMC*, 19.

²⁹³ I. Tzachili, "An Addendum: Were there Sources of Metal Ores on Crete or Not?," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008).

²⁹⁴ Evelyn, *Minoan Crafts* 2, 403.

Smelting was carried out at Chrysokamino and Kephala Petras during the Prepalatial period, and with imported ores at Chrysokamino.²⁹⁵ There is no evidence for smelting or for large-scale ingot production on Crete during the palatial periods, though small ingots were produced from metal rather than ores.²⁹⁶ From as early as the Neolithic, Crete was part of an Aegean trade network which, by the Neopalatial, included the trading of tin and of processed and refined copper as oxhide ingots. Lead isotope studies indicate that by the Neopalatial period copper came largely from Lavrion in Greece, Cyprus and the Taurus Mountains, and later also from Sardinia.²⁹⁷ The source of tin is unknown, but some possibilities include the Iberian peninsula, Afghanistan, and the Balkan peninsula.²⁹⁸ Although oxhide ingots in the wider Aegean were sometimes bronze, those extant from Crete are all unalloyed copper.²⁹⁹ Evidence from Linear B tablets suggests that the importation and internal distribution of metals was under palatial control during much of the Bronze Age.³⁰⁰ The form in which a smith received copper was probably as whole or parts of oxhide or bun ingots. Tin may have come in metallic or mineral form.

Scrap would also have been used, collected from the workshop as spills, offcuts and faulty casts and from the community as blunt and damaged items. Recycling seems to have been carried out at the Unexplored Mansion and at Mochlos.³⁰¹

In Chapter One, we established that Minoan smiths were mixing alloys specifically for the items being made (§1.2.3). The advantage of using an ingot over recycling scrap is that the smith would have had a reasonable idea of the metal's composition, and

²⁹⁵ Chrysokamino: Betancourt, "The Copper Smelting Workshop at Chrysokamino: Reconstructing the Smelting Process."; Kephala Petras: M. Catapotis, Y. Bassiakos, and Y. Papadatos, "Reconstructing Early Cretan Metallurgy: Analytical Evidence from Kephala Petras, Siteia," in *Metallurgy: Understanding How, Learning Why: Studies in Honor of James D. Muhly*, ed. Philip P. Betancourt and Susan C. Ferrence (Philadelphia: INSTAP Academic Press, 2011).

²⁹⁶ Evely, *Minoan Crafts* 2, 346.

²⁹⁷ Evely and Stos, "Aspects of Late Minoan Metallurgy at Knossos."; Betancourt, "Minoan Trade," 221-2; Evely, "Materials and Industries," 390-391.

²⁹⁸ J. D. Muhly, "Sources of Tin and the Beginnings of Bronze Metallurgy," *AJA* 89 (1988): 282-283; G. Rapp Jr., "Copper, Tin and Arsenic Sources in the Aegean Bronze Age," in *MELETEMATA*, ed. Philip P. Betancourt, et al., *Aegaeum* 20 (Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1999), 73.

²⁹⁹ Hakulin, *BLMC*, 19.

³⁰⁰ S. Sherratt, "Circulation of Metals and the End of the Bronze Age in the Eastern Mediterranean," in *Metals Make the World go Round: The Supply and Circulation of Metals in Bronze Age Europe: Proceedings of a Conference held at the University of Birmingham in June 1997*, ed. C. F. E. Pare (Oxford: Oxbow Books, 2000); Evely, *Minoan Crafts* 2, 346; A. Michailidou, "Late Bronze Age Economy: Copper/Bronze in Linear B Script and Material Evidence," in *Colloquium Romanum: atti del XII colloquio internazionale di micenologia, Roma, 20 - 25 febbraio 2006*, ed. Anna Sacconi, et al. (Pisa/Rome: Fabrizio Serra, 2008).

³⁰¹ Unexplored Mansion: Evely, *Minoan Crafts* 2, 338; Mochlos: J. S. Soles, "A Community of Craft Specialists at Mochlos," in *TEXNH*, ed. Robert Laffineur and Philip P. Betancourt, *Aegaeum* 16 (Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1997), 426.

appropriate alloys could be mixed as required. Since oxhide ingots imported to Crete were apparently predominantly unalloyed copper, alloying must have taken place in Crete, and surely by the smiths themselves rather than by palatial administrators, since the smith would have known exactly what alloy was required for the item being produced.

Scraps would need to be identified and sorted to prevent use of an incorrect alloy. For example, a tin bronze which was originally mixed to make weapons, averaging 10% tin during the Neopalatial and up to 14% at Final Palatial Knossos,³⁰² would probably have had too high a tin content for the construction of a vessel which required extensive hammering such as a large hydria or cauldron. The smith could have identified the different alloys by experience. Since the colour of a metal is indicative of its composition, the smith would have been able to see the difference between a low-tin and a high-tin bronze, and failing that could have tested its character with a few blows of a hammer or chisel.

§4.2. Creating the Metal Blank from which a Vessel can be Made

The metal must now be transformed into billet to be hammered. This involves breaking up ingots or scrap and casting the billet in the desired alloy.

§4.2.1. Breaking up Metal

Large ingots and large pieces of scrap would need to be broken into smaller pieces. A method for breaking up ingots described in the 16th century AD by Agricola has been reconstructed and explained by Van Lokeren.³⁰³ The process was successfully carried out by him on a reconstructed LBA copper oxhide ingot. In Agricola's description, cakes of copper are stacked in a furnace with egg-sized rocks between them and those at the bottom are raised on pieces of brick. Thus the heat of the furnace can get between and around the ingots, allowing them to heat more consistently than if they were stacked one upon the other or left flat on the furnace floor. Charcoal and live coals are thrown over the cakes. Within two hours the cakes are heated to the required temperature, removed and hammered until they break into pieces. According to Agricola, the hotter

³⁰² Evely and Stos, "Aspects of Late Minoan Metallurgy at Knossos," 26.

³⁰³ G. Agricola, *De re metallica*, trans. Herbert Hoover and Lou Henry Hoover (New York: Dover Publications, 1950), 503-504; Van Lokeren, "Experimental Reconstruction of the Casting of Copper 'Oxhide' Ingots."

the cakes are, the faster they break up. Van Lokeren found that the high porosity of oxhide ingots played an important role in the success of this process.

The equipment required for this process is a hearth, a means of introducing a draught and a sledgehammer. Hearths and draught-producing equipment are discussed in §4.2.2 below. A small number of extant Minoan bronze hammers might be suitable for this process, though none are from metallurgical contexts.

Bronze socketed sledgehammer head (**figure 107**, above).³⁰⁴

Dimensions 230 x 80 mm. Both faces curved. Weight 7.24 kg. Ayia Triada ?MM III-LM I. The size and weight make it suitable for heavy forging of large items or breaking up ingot material rather than finer metalworking. It would also have been suitable for masonry as Shaw suggests.

Bronze socketed sledgehammer head (**figure 107**, below).³⁰⁵

Dimensions 150 x 80 mm. Both faces curved. Weight 4.157 kg. Ayia Triada ?MM III-LM I. As for the previous hammer, this is more suitable for heavy forging, breaking ingots and masonry than for finer metalworking.

Scrap metal may be broken up with chisels.³⁰⁶ Since cutting up metal plays an important role in vessel construction, this is covered below in §4.6.3.

§4.2.2. Alloying, Melting and Casting

The process of melting and casting copper alloys during the Bronze Age has been well covered in the past.³⁰⁷ The mould is prepared first. The surfaces of the matrix are coated in a substance such as oil or soot which will allow the cast to be removed later. It is then placed in a cooler part of the hearth where it is gently heated. A hot mould prevents molten metal from solidifying before it has reached the full extent of the matrix and also prevents thermal shock in the mould which can make it crack or explode.

³⁰⁴ HM 831; J. W. Shaw, *Minoan Architecture: Materials and Techniques* (Rome: Istituto Poligrafico dello Stato, 1973), 53-54, figs 41.aA, 41.bA; Evely, *Minoan Crafts* 1, 101, no. 13, fig. 44.13; J. W. Shaw, *Minoan Architecture: Materials and Techniques*, 2nd ed. (Padova: Bottega d'Erasmus, 2009), 42-43, figs 39.aB, 39.bA.

³⁰⁵ HM 1253; Evely, *Minoan Crafts* 1, 101, no. 14; Shaw, *Minoan Architecture: Materials and Techniques*, 42-43, figs 39.aA, 39.bB.

³⁰⁶ Evely, *Minoan Crafts* 1, 12.

³⁰⁷ R. F. Tylecote, *History of Metallurgy* (London: Institute of Materials, 1992), 21-35, 38-41; Evely, *Minoan Crafts* 2, 346-365.

The crucible, loaded with metal, is placed either on top of a bed of burning charcoal or inside the hearth, under the charcoal.³⁰⁸ A reducing atmosphere is maintained since oxygen and hydrogen, which molten copper dissolves on exposure to air, create water vapour which causes porosity upon solidification.³⁰⁹ Tin or arsenic in bronzes reduce this tendency owing to their anti-oxidizing characteristics. If the crucible is underneath the charcoal fuel, this will provide a reducing atmosphere. If it is on top of the charcoal, a flux or a covering of charcoal or wood shavings may be used to prevent oxidization.³¹⁰

A draught is introduced to the hearth with bellows or blowpipes to increase the temperature of the fuel. If the metal is to be alloyed, the alloying component, measured out beforehand, may be added as mineral or metal either initially, before heating begins, or at the molten stage.³¹¹ Stirring molten copper and copper alloys with a piece of wood creates a chemical reaction which reduces copper oxides in the metal. The liquefied metal is poured into the mould, which is subsequently opened to retrieve the casting.

The requirements are a hearth, fuel, a crucible, a means for providing a draught, tongs, a mould, flux and a means for measuring out alloy components.

The Hearth

No extant Minoan metallurgical installations have hearths which can be definitively linked to metallurgical activities, so it is difficult to reconstruct exactly what form metalworking hearths took. The simplest open hearth may have been formed with burning charcoal sitting in a mound on the ground, or perhaps contained in a shallow depression. Hearths like this may not leave much evidence. Some metalworking installations show little evidence of the existence of a hearth other than a burned area or some scattered charcoal (see Chapter Five).

Tylecote states that a hearth need only be some means of containing the fuel, even a ring of stones.³¹² A few such simple hearths have been linked to metallurgical contexts. A clay-lined hearth in Pillar Hall H of the Unexplored Mansion at Knossos (§5.2) is a scoop walled on three sides with clay enclosing a space 400 x 550 mm and 200 mm high (**figure 108**).³¹³ Shaw names this type a pi-shaped hearth.³¹⁴ Evelyn points out that

³⁰⁸ Tylecote, *History of Metallurgy*, 38; Evelyn, *Minoan Crafts* 2, 346.

³⁰⁹ Brown, ed. *Fosco Non-Ferrous Foundryman's Handbook*, 232.

³¹⁰ Evelyn, *Minoan Crafts* 2, 346.

³¹¹ *Ibid.*, 346.

³¹² Tylecote, *History of Metallurgy*, 21, 38.

³¹³ M. R. Popham, *The Minoan Unexplored Mansion at Knossos*, 2 vols., BSA Suppl. 17 (Athens: British School of Archaeology at Athens, 1984), 121, pl. 29.e; Catling and Catling, "The Bronzes and Metalworking Equipment," 206; Evelyn, *Minoan Crafts* 2, 338, fig. 137.1.

it does not show signs of high temperatures, nor any metal dribbles to indicate its use for metalworking.³¹⁵ He also argues that its size would have limited its use to crucible operations. Since most Minoan metalworking was limited to small-scale processes, this does not necessarily exclude the hearth from use as a smith's hearth.

Some of the pi-shaped hearths at Kommos (§5.4) have been proposed for metallurgical use (**figure 109**).³¹⁶ These are enclosed by three low walls made of clay, or stone or mud brick uprights which are sometimes lined with clay and have similar dimensions to that at the Unexplored Mansion. Many hearths of this type exist at Kommos, but most appear to have been for domestic use. As in the case of the hearth at the Unexplored Mansion, none shows direct evidence for metallurgical use. Another possible hearth at Poros-Katsambas (§5.10) consists of a clay-lined rock hollow.³¹⁷ Evely lists more possible hearths at Malia and Chania which are similar in structure to those at the Unexplored Mansion and Kommos, but these are not associated with any other metallurgical material.³¹⁸

Portable hearths may have been used. These are depicted in the New Kingdom tomb of Rekhmire (**figure 110**). Evely proposes that a ceramic vessel from Malia may have had such a function. This vessel is cylindrical with high walls, a cut-out at the front and a separate chamber for storing charcoal.³¹⁹ Large crucibles could be used as portable hearths; Brogan suggests this for some large crucibles from Mochlos.³²⁰ For melting, metal is placed at the bottom, fuel placed over the top, and artificial draught applied.³²¹

For melting larger volumes of metal, an enclosed furnace could have been used, but there is little evidence of any such structure for metalworking in Crete. A fingered kiln at Zakros and horseshoe-shaped kiln at Phaistos were both interpreted by excavators as potential metalworking furnaces because of the presence of slag-like materials.³²² Both

³¹⁴ M. C. Shaw, "Late Minoan Hearths and Ovens at Kommos, Crete," in *L'habitat Égéen préhistorique*, ed. Pascal Darcque and René Treuil, BCH Suppl. 19 (Athens: École française d'Athènes, 1990), 248.

³¹⁵ Evely, *Minoan Crafts* 2, 338, 341.

³¹⁶ Shaw, "Hearths and Ovens."; H. Blitzer, "Minoan Implements and Industries," in *Kommos I: Part 1*, ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 1995), 501.

³¹⁷ N. Dimopoulou, "Workshops and Craftsmen in the Harbour-Town of Knossos at Poros-Katsambas," in *TEXNH*, ed. Robert Laffineur and Philip P. Betancourt, Aegaeum 16 (Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1997), 435.

³¹⁸ Evely, *Minoan Crafts* 2, 365.

³¹⁹ P. Demargne and H. G. de Santerre, *Maisons I - Exploration des maison et quartiers d'habitation, 1921-1948*, ÉtCrét 9 (Athens: École Française d'Athènes, 1953), 91-92, pls 39.1-2 and 58.4; Evely, *Minoan Crafts* 2, 365.

³²⁰ Brogan, "Metalworking at Mochlos," 163.

³²¹ J. E. Rehder, *The Mastery and Uses of Fire in Antiquity* (Montreal & Kingston: McGill-Queen's University Press, 2000), 89-90.

³²² Evely, *Minoan Crafts* 2, Phaistos: 301, type 1(a), no. 3, Zakros: 304, type 2, no. 9, fig. 122.

are more suitable as pottery kilns, however, and neither is otherwise within a metallurgical context. The slags have apparently never been confirmed as such.

The Fuel

Charcoal is assumed to be the primary fuel used for metallurgy in antiquity, but there are other possibilities. A wood fire can reach useful temperatures with the addition of an artificial draught, but it is difficult to maintain a steady temperature.³²³ Timber which makes the most suitable charcoal for use in a hearth is ideally slow-burning; such timbers tend to be hardwoods. Olive and oak might be suitable, and were common in Crete during the Bronze Age, as they are today.³²⁴ Pine, which was also common, is less suitable since it burns quickly. Olive wood was found to have been used as fuel in several hearths at the Artisans' Quarter and at Chalinomouri.³²⁵ Schoch and Ntinou suggest that agricultural prunings may have been used here. Dung has been used as fuel for metalworking in recent centuries, though Forbes says that it is inferior.³²⁶ Other possible fuels include olive pressings, chaff, reeds, straw and bones.³²⁷

The Draught

Three methods for producing draught may have been used: a blowpipe, a pipe with skin-bellows, or pot-bellows.³²⁸ Pot-bellows, used since the Prepalatial period, have come from several sites.

†Clay pot-bellows (**figure 111**).³²⁹ Maximum bowl diameter 350 mm, height 140 mm, nozzle length 340 mm. Coarse-grained clay with organic temper, slip on surface. Bowl is wheel-made, nozzle made by slab technique. Kommos, LM (§5.4.5).

The bowl of the pot is covered with a skin which is pumped up and down to supply a draught. Pot bellows may have been used in pairs and pumped by hand, as Blitzer proposes for Prepalatial pot bellows found at Chrysokamino (**figure 112**).³³⁰

³²³ Ibid., 352.

³²⁴ W. H. Schoch and M. Ntinou, "Wood Charcoal," in *Mochlos IC*, ed. Jeffrey S. Soles and Costis Davaras (Philadelphia: INSTAP Academic Press, 2004), 132.

³²⁵ Ibid., 134. These may be domestic hearths.

³²⁶ R. J. Forbes, *Studies in Ancient Technology*, vol. 8 (Leiden: E. J. Brill, 1964), 105.

³²⁷ Ibid., 104-105; Evely, *Minoan Crafts* 2, 352.

³²⁸ Evely, *Minoan Crafts* 2, 363.

³²⁹ Blitzer, "Minoan Implements and Industries," 508, no. M 42, pls 8.80A, 8.105.

³³⁰ Betancourt and Muhly, "The Pot Bellows," 127.

Alternatively, they may have been pumped with the feet, a method depicted in the Egyptian New Kingdom Tomb of Rekhmire (**figure 113**).

Tuyères, large clay nozzles used for directing the draught from bellows, have been found in metallurgical contexts at Kommos (§5.3), Malia (§5.6.4 and §5.6.5), Palaikastro (§5.9) and Poros-Katsambas (§5.10.2). These may have been used with pot- or skin-bellows. A clay tube from the Unexplored Mansion, which Catling describes as a nozzle for skin-bellows, was probably for some other purpose.³³¹ The presence of tuyères without pot-bellows, as at Palaikastro, may indicate the use of skin-bellows, since nothing would survive other than the tuyère it was attached to.

Blowpipes are suitable for small-scale operations. A blowpipe made from a reed would leave no evidence unless it had been tipped with a ceramic nozzle to protect it from the fire. Tuyères cannot be used for blowpipes since, according to Rehder, blowpipe nozzles must have an internal diameter of 5 to 10 mm whereas bellows tuyères have an inner diameter more than double this.³³² Small nozzles have not survived, which may indicate that blowpipes were used without nozzles. Egyptian smiths are depicted using blowpipes with nozzles and Colombian smiths in the 16th century AD apparently without nozzles (**figures 110 and 114**).

Crucibles

Several types of crucible were used in Crete.³³³ The basic shapes are a bowl on a low, pierced stem, and shallow bowl forms with a pouring lip or bridge-spout. All are open forms without lids. They are made from clay with chaff or some other organic temper, though one listed by Evely is stone.³³⁴ According to Evely, the smallest of the crucibles had the capacity for casting 70 g of bronze, suitable for producing the smallest tools or working in precious metals; the average crucible 1.9 kg, enough for producing one or two double-axes; and the largest 4.5 kg, providing enough metal for multiple casts of tools, or for the largest swords or panels of cauldrons.³³⁵ The possible use of large crucibles as hearths has been discussed above.

³³¹ Popham, *The Minoan Unexplored Mansion at Knossos*, 26, no. H 58, pls 199.i and 207.5; Catling and Catling, "The Bronzes and Metalworking Equipment," 220, no. H 58; Evely, *Minoan Crafts* 2, 363.

³³² J. E. Rehder, "Blowpipes versus Bellows in Ancient Metallurgy," *JFA* 21, no. 3 (1994): 349.

³³³ Evely, *Minoan Crafts* 2, 346-352.

³³⁴ *Ibid.*, 349-351, 352, fig. 140.

³³⁵ *Ibid.*, 352.

Tongs

Tongs are required for shifting fuel and for placing the crucible in and removing it from the hearth. Crucibles with pierced stems were designed to take a rod or stick through the stem but, Evely points out, may still have required some other means to support the top.³³⁶ Tylecote, however, cites a demonstration of the use of such a crucible where a stick through the stem was sufficient for both picking up and pouring.³³⁷ Green withies are thought to have been used by New Kingdom Egyptian smiths to manipulate crucibles of molten metal (**figure 115**).³³⁸ Another method is to use hand-held stone discs to pick up the hot crucible, as was apparently the case in Old Kingdom Egypt.³³⁹ Evely believes that this method is unlikely, and I am inclined to agree, since the temperatures, in the vicinity of 1000°C, would surely make this impractical. Inca smiths used wooden or copper rods.³⁴⁰ Any of these methods is also suitable for shifting fuel.

Several sets of bronze tongs are extant from Crete. They range between 72 and 450 mm long and most are made from rod or strip which is bent double with the handle end worked into a ring; this would act as a spring. One set is made from two separate rods which are joined at the handle end.³⁴¹ Larger sets of tongs could have been used for moving crucibles, adjusting hot fuel and manipulating hot metal objects in the hearth. No large tongs come from metallurgical contexts.

Bronze tongs (**figure 116**).³⁴² 350 mm long, rod of rectangular section bent in half, handle end bent into a ring-shape. One tip flat, the other round. Mochlos House C.3, LM IB (§5.7.3). These and another pair of tongs were found in a deposit which included several other finished metal items including a sistrum, knives and daggers, chisels and bronze bowls. Soles identifies this collection as a trader's hoard. The lack of any metallurgical evidence in the vicinity indicates that this is probably correct.

³³⁶ Ibid., 351.

³³⁷ Tylecote, *History of Metallurgy*, 22-23.

³³⁸ G. A. Wainwright, "Rekhmire's Metal-Workers," *Man* 44, no. 4 (1944): 94.

³³⁹ Evely, *Minoan Crafts* 2, 365.

³⁴⁰ G. d. I. Vega, *Royal Commentaries of the Incas and General History of Peru*, trans. Harold V. Livermore, 2 vols. (Austin: University of Texas Press, 1966), 131.

³⁴¹ Evely, *Minoan Crafts* 2, 365, no. 4.

³⁴² Brogan, "Metalworking at Mochlos," 165, fig. 6, left; J. S. Soles, "Metal Hoards from LM IB Mochlos, Crete," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008), 151.

Small sets of tongs similar to modern metalsmithing tweezers are suitable for smaller work, particularly jewellery-making. Though impractical for lifting and manipulating loaded crucibles, they may have been used for shifting fuel.

†Bronze tongs/tweezers (figure 117).³⁴³ Length 72 mm. Blade flares out from handle-end to 18 mm wide and 1.5 mm thick. Tips bent inwards to improve grip. Unexplored Mansion, LM II (§5.2). Catling also suggests that these may have been depilatory tweezers.

Moulds

Minoan smiths used open, bivalve and three-part stone moulds, and open moulds in clay as well as clay moulds for lost-wax casting. A single example of a copper or bronze mould for a double axe is known (figure 118).³⁴⁴ Evely has catalogued many moulds.³⁴⁵

Stone moulds are the most numerous of the extant moulds. This may be because, since stone is more durable than clay, these moulds have survived. Stone moulds are made from schist, limestone, steatite and chlorite. One fragment from Knossos is reportedly of sandstone.³⁴⁶ Open, one-piece stone moulds are often for casting billets and frequently have matrices for several different items. One from LM IB Gournia is four-sided and has matrices for variously sized chisels and bars (figure 119).³⁴⁷ Open stone moulds for small jewellery items also exist, but it is difficult to determine whether they were for metal or for glass and faience, or whether they were used as dies for foil.³⁴⁸ A single mould might be used for all of these.³⁴⁹ Very shallow matrices are dies for embossing foil.

Most of the extant stone bivalve moulds were for casting double-axes (figure 120). Using a bivalve mould enabled a core to be put in place to create the handle socket.³⁵⁰

³⁴³ Catling and Catling, "The Bronzes and Metalworking Equipment," 215, no. L 126, pls 198.h and 205.1; Evely, *Minoan Crafts* 2, 365, no. 6.

³⁴⁴ HM 1466; Evely, *Minoan Crafts* 1, 51, fig. 21; Evely, *Minoan Crafts* 2, 358, no. 17.

³⁴⁵ Evely, *Minoan Crafts* 2, 356-361.

³⁴⁶ *Ibid.*, 360, no. 31.

³⁴⁷ HM 397; H. B. Hawes et al., *Gournia, Vasiliki and Other Prehistoric Sites on the Isthmus of Hierapetra, Crete: Excavations of the Wells-Houston-Cramp Expeditions, 1901, 1903, 1904* (Philadelphia: The American Exploration Society, Free Museum of Science and Art, 1908), 32, pl. 3.67; Evely, *Minoan Crafts* 2, 356, no. 3, fig. 142.3.

³⁴⁸ Evely, *Minoan Crafts* 2, 415.

³⁴⁹ Laffineur, "Craftsmen and Craftsmanship," 192-193.

³⁵⁰ e.g. a mould from Malia, northwest area of the palace, MM III: F. Chapouthier and P. Demargne, *Palais III - Troisième rapport*, *ÉtCrét* 6 (Athens: École française d'Athènes, 1942), 56-58, no. A.1, fig. 37, pl. 52.1b and c; O. Pelon, "Minoan Palaces and Workshops: New Data from Malia," in *The Function of the Minoan Palaces: Proceedings of the Fourth International Symposium at the Swedish Institute in*

The mould pieces often have notches around their edges where binding was used to hold the halves together. Copper strips, which have been found at several metallurgical sites, were probably used to tie the halves together.³⁵¹ The moulds also often have some holes for locating pins or pegs to hold the two pieces together correctly.

Simpler stone bivalve moulds were used to cast basic shapes. For these moulds, the matrix and a pouring channel were carved into a flat slab and another plain flat slab was used as a cover.³⁵² The two were bound together and turned with the opening of the pouring channel uppermost, to allow the molten metal to be poured in. They were often used with locating pins. There are extant moulds for casting billets, tools and jewellery (**figure 121**). Two bivalve stone moulds from Malia for casting disc-billets have been suggested for vessel-production.³⁵³

†Talc schist bivalve mould for an ovoid disc-billet (**figure 122**).³⁵⁴ 230 x 20 mm. Matrix for ovoid disc ?160 x 5-6 mm. The matrix is open on one end, creating a pouring channel. Holes have been drilled through two corners of the mould for locating pins. The other half of the mould, which is now missing, would probably have been a plain slab with holes for the locating pins. Malia, northwest area of palace, MM III (§5.5).

Three-part stone moulds were also used for casting bezel rings (**figure 123**).

Clay was used to make lost-wax moulds and open moulds, though I am aware of only two extant clay open moulds (**figure 124**). Clay moulds deteriorate with casting, so open clay moulds may have been intended only for single use. Both extant moulds are for small billets.

Lost-wax casting may be direct or indirect. For direct casting, a single wax is made by hand and coated with clay. Funnels and risers are incorporated into the initial wax model. The wax is subsequently burned out so that molten metal can be poured into the resulting matrix. For indirect casting, the wax is cast in a mould and subsequently used to make the lost-wax mould. The benefit of indirect casting is that it allows identical

Athens, 10-16 June, 1984 ed. Robin Hägg and Nanno Marinatos (Stockholm: Svenska institutet i Athen, 1987); Evelyn, *Minoan Crafts* 2, 358, no. 19, fig. 143.19, pl. 87.1.

³⁵¹ Catling and Catling, "The Bronzes and Metalworking Equipment," 204, 218; Evelyn, *Minoan Crafts* 2, 362.

³⁵² LM I Gournia mould cover: Hawes et al., *Gournia, Vasiliki and Other Prehistoric Sites*, 32, pl. 3.55; LM II Quartier Mu mould cover J.-C. Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, ÉtCrét 32 (Athens: École Française d'Athènes, 1996), 55, no. C28, pl. 53.d.

³⁵³ Renfrew, *The Emergence of Civilisation: the Cyclades and the Aegean in the Third Millennium B.C.*, 317.

³⁵⁴ HM 3227; Chapouthier and Demargne, *Palais III*, 65, no. 1, pls 16 and 52.2a; Pelon, "New Data from Malia," Evelyn, *Minoan Crafts* 2, 356, no. 6, fig. 142.6.

multiples to be produced. Indirect casting was very common during the Roman period, but Rolley says that it was rare before then.³⁵⁵

Because the direct casting process involves the mould being broken after use, lost-wax moulds exist only in fragments. Most of those extant were used to cast double axes. Many of these were recovered from the LM IIIA-B installations in the houses at Kommos (§5.4), where double-axe production was apparently a local industry (**figure 125**).³⁵⁶ A smaller number from other workshops and installations were used to produce chisels and other tools, billets, vessel handles and jewellery items such as beads and pendants.

The most complex lost-wax mould extant of Minoan attribution is for the hand of a statue, dated to MM I-II (**figure 126**). This mould is advanced compared to all other Minoan lost-wax moulds, which are for solid shapes or for shapes with a simple core which passes through the item. The hand would have been hollow and with a wall thickness of only 2 mm, but no extant Minoan cast metal objects have hollow interiors or material so thin on a large scale. Hollow lost-wax casting is virtually unknown in the entire Aegean during the Bronze Age. Laviosa proposes that this mould may have been a one-off experiment.³⁵⁷

The only extant moulds which may have been used for vessel billet production are bivalve stone moulds. However, open stone and clay moulds could have been used, and lost-wax casting, used to produce vessel appendages (see §4.6.1 below), could easily have been used to produce billets. This process would have been particularly useful for casting billets which include a provision for an appendage. Also, since any one workshop must have been producing vessels of different sizes and shapes, it would be preferable to use lost-wax casting since this allows for the variations in size and shape which would have been required for the different billets. Though moulds made from stone can be used repeatedly, any one matrix can produce only one size of billet.

Flux

The absorption of gases into molten metal must be reduced to prevent porosity in a cast, since the resulting material is unsuitable for hammering. A flux can help, usually by dissolving oxygen, and is added to the crucible along with the metal or at some stage during heating before the metal becomes liquid. Fluxes suggested by Evelyn include

³⁵⁵ Rolley, *Greek Bronzes*, 27.

³⁵⁶ Blitzer, "Minoan Implements and Industries," 506-507.

³⁵⁷ Laviosa, "Una Forma Minoica per Fusione a Cera Perduta."

bone ash, haematite, oils, fats, honey, resins, dung and urine preparations, beeswax, soda, natron, and borax.³⁵⁸ Ogden says that salt makes an effective flux, particularly sea salt, because of its impurities.³⁵⁹

Measuring

Alloying requires measuring the components for the alloy. Scale pans, found around the Aegean, may have been used for measuring alloy components. The pans are between 45 and 140 mm in diameter and usually have four small, equally spaced holes near the rim for suspension. Only one set of these pans comes from a metallurgical context, at the Unexplored Mansion. A set of scale pans from House C3 at Mochlos which was amongst metalworking tools and other intact bronze items was probably part of a trader's hoard (see §5.7.3 below).³⁶⁰

†Pair of bronze scale pans (fragments).³⁶¹ Reconstructed dimensions 85 x 0.3 mm. Unexplored Mansion, LM II (§5.2).

§4.3. Annealing

There has been little written on the procedure used to anneal metals in antiquity, though the underlying physical principles are well understood.³⁶² Assuming that the hearth used is the same as that used for casting, the metal could simply be buried in the burning fuel. If left for long enough, the metal may anneal unassisted, but the addition of a draught would speed up the process. Bellows are unnecessary, since they are capable of producing temperatures over 1600°C,³⁶³ and copper or bronze anneal between 200 and 800°C. Blowpipes can achieve the lower temperatures, as can a breeze blowing over the hearth.

Papadimitriou has carried out an extensive study of the benefits of quenching various bronzes in water to improve their workability (see §1.2.3 above).³⁶⁴ Containers for quenching which have been suggested include a bronze basin at the Unexplored

³⁵⁸ Evelyn, *Minoan Crafts* 2, 353, 387.

³⁵⁹ Ogden, *Jewellery of the Ancient World*, 64.

³⁶⁰ Soles, "Metal Hoards," 151.

³⁶¹ Popham, *The Minoan Unexplored Mansion at Knossos*, 48, no. L 67, pls 197.f and 203.6-7; Catling and Catling, "The Bronzes and Metalworking Equipment," 206.

³⁶² Papadimitriou, "Simulation Study of Ancient Bronzes."

³⁶³ Rehder, "Blowpipes versus Bellows in Ancient Metallurgy," 349.

³⁶⁴ Papadimitriou, "Simulation Study of Ancient Bronzes."

Mansion and a larnax at Kommos.³⁶⁵ Any container of the appropriate size for the object being annealed would do.

The need to remove oxides from the metal's surface before hammering is frequently overlooked in archaeometallurgical studies. Burying the metal in the fuel during annealing would reduce oxidization but would not eliminate it completely, since some would occur when the hot metal is exposed to air after its removal from the hearth. There is no way to determine exactly what methods were used by Minoan smiths. Ogden lists a variety of ancient pickle recipes with acidic ingredients such as vinegar, brine and urine.³⁶⁶ The third-century AD Leyden Papyrus X suggests quenching copper in bird dung.³⁶⁷ This would pickle the copper because of the high concentration in bird dung of uric acid, which has a corrosive effect on copper.³⁶⁸ Other mechanical means may also be employed, such as scraping or grinding the oxides off the surface, though this is more labour intensive and less effective, since oxides in pits or tight spots would be left behind. It also causes significant material loss, since a vessel might need anywhere between five and sixty annealing rounds, each followed by oxide removal.

§4.4. Shaping

In Chapter Three, various methods which have been proposed for vessel-making were evaluated. The most likely of these is hammering the vessel from a thick billet by spiral-forging or sinking to create the concave, thin-walled form and subsequently raising the walls if necessary. The equipment for shaping are hammers and surfaces on which the metal is hammered: anvils, stakes and sinking hollows.

§4.4.1. Hammers

The types of hammer used for vessel forming today were discussed in Chapter Two (§2.1.4). Materials which have been proposed for hammers used for vessel-making or sheet-working in antiquity include bronze, stone, wood, bone and horn. Only bronze and stone hammers remain from Minoan contexts, and only stone from metallurgical

³⁶⁵ Catling and Catling, "The Bronzes and Metalworking Equipment," 207; Blitzer, "Minoan Implements and Industries," 527.

³⁶⁶ Ogden, *Jewellery of the Ancient World*, 87.

³⁶⁷ E. R. Caley, "The Leyden Papyrus X: An English Translation with Brief Notes," *Journal of Chemical Education* 3 (1926): 1159.

³⁶⁸ E. Bernardi et al., "The Effect of Uric Acid on Outdoor Copper and Bronze," *Science of the Total Environment* 407 (2009).

contexts. Bone and horn hammers may have been used, but none have been reported from excavations. Wooden hammers are also a possibility but have not survived.

Bronze Hammers

A LC III (12th-century BC) Cypriot socketed double-hammer is suggested by Catling to have been a raising hammer.³⁶⁹ It is the only bronze hammer from the Aegean Bronze Age that I know of which seems deliberately made for raising metal. Its resemblance to modern raising hammers is striking (cf. **figures 127 and 128**). Catling lists a small number of other hammers from the Aegean, which may have been raising hammers, though these do not resemble modern raising hammers and might have many other uses.

A small number of bronze hammers have been found in Crete. Of these, only a few are suitable for metalworking and, as far as I am aware, none comes from a metallurgical context.

Bronze mallet with two rectangular faces (**figure 129**).³⁷⁰ Dimensions 66 x 38 x 30 mm. Circular handle cast in one piece with the head, preserved length 16 mm, diameter 24 mm. Psychro, modern or MM III-LM. Suitable for forging.

Bronze hammer/T-stake (**figure 130**).³⁷¹ Head dimensions 106 x 16 mm. Circular handle cast in one piece with head 20 mm in diameter, total hammer length 133 mm. One face is ovoid and domed, the other flat and octagonal to circular in section. Weight 650 g. Samba Pediados, date unknown. Suitable for forging and sinking, though because so much of its weight is in the handle, it would not be a very efficient hammer, since the smith's arm would tire quickly. It could also be used as an anvil or stake (see §4.4.2).

Bronze rectangular block (**figure 131**).³⁷² Dimensions 150 x 20 mm. Tapering toward the ends with round, curved faces. Malia MM III-LM

³⁶⁹ BM 1897,0401.1468; Catling, *CBMW*, 100, no. 1, 278-281, pl. 11.c.

³⁷⁰ AshM AE73; J. Boardman, *The Cretan Collection in Oxford: The Dictaeon Cave and Iron Age Crete* (Oxford: Clarendon Press, 1961), 52, no. 225 and Appendix I, fig. 24.225, pl. 17; Evely, *Minoan Crafts* 1, 101 no. 2, fig. 44.2.

³⁷¹ HM 1795; J. Deshayes, *Les outils de bronze, de l'Indus au Danube (IVe au IIe millénaire)*, vol. 1 (Paris: Librairie Orientaliste P. Geuthner, 1960), 298, no. 2321, pls 40.3, 63.1; Catling, *CBMW*, 100; Evely, *Minoan Crafts* 1, 101, no. 3, fig. 44.3, pl. 22.3.

³⁷² J. Deshayes and A. Dessenne, *Fouilles exécutées à Mallia: Exploration des maisons et quartiers d'habitation (1948-1954)*, *ÉtCrét* 11 (Athens: École Française d'Athènes, 1959), 70-71, pl. 20.1; Evely, *Minoan Crafts* 1, 97-101, no. 1, fig. 44.1.

IB. For hammering, this could be held in the hand or have a handle lashed to it. It would be suitable for forging and sinking, and possibly for raising. Deshayes and Dessenne described it as an ingot, but Evely suggests that it may have been a blank for working.

Small socketed bronze hammer (**figure 132**).³⁷³ Dimensions 75 x 26 mm, oval socket-hole 24 x 21 mm. Curved horizontal face 30 x 14 mm, curved vertical face 37 x 10 mm. Provenance unknown, date ?LM I. The horizontal face is suitable for raising small items, while the vertical face might suit some specialised forging and sinking tasks. Davaras suggests that it is probably a woodworking tool.

Small socketed bronze hammer (**figure 133**).³⁷⁴ Dimensions 100 x 20 mm, socket-hole diameter 10 mm. Domed square face 17 x 15, curved horizontal face 15 x 6. Malia, Quartier Mu, MM II or LM III. The square face is suitable for forging small items, the larger for raising small items.

A stone mould from MM III –LM I Phaistos contains a matrix for a hammer which Catling suggests may have been used for raising; Evely suggests that it may have been for jewellery or for metalwork.³⁷⁵

Stone Hammers

Stone hammers are commonly found in both metallurgical and domestic contexts. Shaw suggests that they were probably commonly used by carpenters and masons.³⁷⁶ Hafting of tools was known to the Minoans, as illustrated not only by the bronze hammers listed above but also by the many extant bronze double-axes, but stone hammers rarely have shaft holes. Those which are extant do not come from metallurgical contexts.

Stone hammers come in several forms. Some are deliberately cut. Mace-heads and mallets have handle sockets and are often made from decorative stone. For the most

³⁷³ CM M41; C. Davaras, "Bronze Double Axes," in *Minoan and Greek Civilization from the Mitsotakis Collection*, ed. Lila Marangou (Athens: N. P. Goulandris Foundation - Museum of Cycladic Art, 1992), 266, no. 331.

³⁷⁴ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 118, no. M 78/B 1, pl. 43.k.

³⁷⁵ Catling, *CBMW*, 100; Evely, *Minoan Crafts* 1, 102, fig. 45.

³⁷⁶ Shaw, *Minoan Architecture: Materials and Techniques*, 44.

part, these probably served ceremonial rather than utilitarian purposes.³⁷⁷ Only one shaft-hole stone hammer I am aware of would have been suitable for raising.

Serpentine socketed hammer (**figure 134**).³⁷⁸ Dimensions 69 x 51 x 27-40 mm. Handle socket diameter 20 mm. Two domed faces, one round, the other ovoid horizontally. Malia, Quartier Mu, outside the area of the workshops. The round face would be excellent for sinking, and the ovoid face for sinking, forging and perhaps raising.

Unmodified stones were more commonly used for hammering. Shaw says that these may be overlooked since they can only be distinguished from naturally occurring stones by the presence of wear from percussion.³⁷⁹ Unmodified stone hammers can be generally categorised as cobbles, pestle-type rods or pebbles. Some of these tools also appear to have been used for finishing processes, as indicated by flattened and faceted faces.

Cobbles are large, smooth stones which fit comfortably in one hand. They may be spherical, discoid, ovoid, triangular or trapezoidal and seem to be of whichever variety of stone was available, including sandstone, limestone, and igneous varieties.³⁸⁰ These would be suitable for all hammering processes, forging, sinking and raising, according to the shape of the stone. They would also serve well for striking punches, chisels and similar tools. Numerous cobble hammers or pounders have been identified amongst metallurgical material. Some of these are described here to illustrate the forms and varieties found.

†Igneous spherical cobble (**figure 135**).³⁸¹ Diameter 64-68 mm, weight 360 g. Knossos, Unexplored Mansion, LM II (§5.2).

†Marble discoid cobble.³⁸² Dimensions 70 x 30 mm, weight 220 g. Knossos, Unexplored Mansion, LM II (§5.2).

†Limestone spherical cobble.³⁸³ Diameter 80-110 mm. Malia, Quartier Mu, Founder's Workshop, MM II (§5.6.1).

³⁷⁷ Shaw, *Minoan Architecture: Materials and Techniques*, 54.

³⁷⁸ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 118, pl. 40.c.

³⁷⁹ Shaw, *Minoan Architecture: Materials and Techniques*, 43.

³⁸⁰ Evely, *Minoan Crafts* 1, 111.

³⁸¹ Popham, *The Minoan Unexplored Mansion at Knossos*, 87, no. P 137, pl. 208.10.

³⁸² *Ibid.*, 37, no. H 217, pls 208.10 and 227.2.

³⁸³ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 52, no. C 9 (B 81/C 10), pl. 41.b.

Deliberately-made pestles and elongated stones of pestle-type are made from a variety of stone types including limestone and marble (rarely), sandstone, and igneous stones, especially andesite and related fine-grained igneous types.³⁸⁴ These have been found at several metallurgical sites. A small number are listed here.

†Marble pestle (**figure 136**).³⁸⁵ Dimensions 68 x 42 mm, weight 200 g. Knossos, Unexplored Mansion, LM II (§5.2).

†Marble pestle.³⁸⁶ Length 72 mm, diameter tapering from 23 to 47 mm, weight 240 g. Knossos, Unexplored Mansion, LM II (§5.2).

†Limestone pestle.³⁸⁷ Dimensions 100 x 19 mm. Malia, Quartier Mu, South Workshop, MM II (§5.6.2).

†?Limestone pestle (**figure 137**).³⁸⁸ Dimensions 154 x 60 mm. Malia, Quartier Mu, Founder's Workshop, MM II (§5.6.1).

Pebbles come in all variety of shapes, sizes and rock types. It is not necessary to list individual finds here. They frequently show signs of percussion and abrasion. These might be useful for hammering difficult-to-reach areas on a vessel which are inaccessible with a larger stone.

The working edge of the so-called 'neolithic' axes may have been suitable for raising, although they were probably no longer being produced by the Neopalatial period.³⁸⁹ One excellent example of this type of tool within a metallurgical context exists.

†Igneous 'neolithic' axe (**figure 138**).³⁹⁰ Dimensions 55 x 42 x 12 mm. Knossos, Unexplored Mansion, LM II (§5.2).

Doumas suggests that during the EBA in the Aegean stone hammer-axes could have been used for metalsmithing (**figure 139**).³⁹¹ While the hammer face of the tool would

³⁸⁴ Evelyn, *Minoan Crafts* 1, 111.

³⁸⁵ Popham, *The Minoan Unexplored Mansion at Knossos*, 59, no. M 40, pl. 209.13.

³⁸⁶ *Ibid.*, 80, no. P 15.

³⁸⁷ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 62, no. D 6 (M 81/C 10).

³⁸⁸ *Ibid.*, 48, no. C 2 (B 82/ C 7), pl. 41.a.

³⁸⁹ D. Evelyn, "The Other Finds of Stone, Clay, Ivory, Faience, Lead etc.," in *The Minoan Unexplored Mansion at Knossos*, ed. M. R. Popham, BSA Suppl. 17 (Athens: British School of Archaeology at Athens, 1984), 237.

³⁹⁰ Popham, *The Minoan Unexplored Mansion at Knossos*, 31, no. H 101, pl. 218.1; Evelyn, "The Other Finds," 237.

³⁹¹ C. G. Doumas, "Searching for the Early Bronze Age Aegean Metallurgist's Toolkit," in *Metallurgy, Understanding How, Learning Why: Studies in Honour of James D. Muhly*, ed. Philip P. Betancourt and Susan C. Ferrence (Philadelphia: INSTAP Academic Press, 2011), 176.

have uses for metalsmithing, the axe face would be almost useless. There are no metal items produced by the Minoans which required the use of a sharp, narrow, vertical hammer face. It seems unlikely that a smith would use a hammer with only one useful face. Hammer-axes would be more suitable for working wood.

Wooden Hammers

Wooden hammers have not survived, but must have been common. The ability of wood to be carved into shape makes it very versatile, and some hardwoods are durable enough to be comparable to stone. Some wooden hammers from other Bronze and Iron Age peoples of types which Minoans might also have used are reviewed here.

Some mallets from New Kingdom Egypt are a promising possibility (**figure 140**).³⁹² The head and handle are carved from a single piece of wood and the top edge of the head has a ridge which is similar in shape to a cross-peen, so it could be used for raising. The same hammer is used with chisels by modern carpenters for modelling wood. Another wooden mallet common today is the basic cylindrical wooden mallet-head with a shaft-hole to take a handle such as one from the Iron Age Breidden Hillfort (**figure 141**).³⁹³ This mallet could be adapted for raising by carving one face into a wedge shape. Another wooden hammer carved from the junction of a slim trunk and branch of a tree uses the natural angled join of the branch to the trunk to form the head and handle (**figure 142**). This type has been found at Neolithic Meare Heath and Bronze Age Flag Fen.³⁹⁴ This form is an adaptation of an adze or axe handle, where a stone head is tied to the working end. This type may have been suitable for raising thin metal. Durable hardwoods are most suitable for hammers.

Hammers: Summary

The scarcity of bronze metalworking hammers not only in Crete but also in the wider Aegean indicates that they were rare. It is possible that bronze hammers did not survive because they were recycled. However, if one considers the relative abundance of other bronze tool types, it seems that if bronze hammers were common, there ought to be

³⁹² G. Killen, *Ancient Egyptian Furniture*, vol. 1 (Warminster: Aris & Phillips, 1980), 18, no. 20, pl. 16.

³⁹³ W. J. Britnell and C. Earwood, "Wooden Artefacts and Other Worked Wood from Buckbean Pond," in *The Breidden Hillfort*, ed. C. R. Musson (London: Council for British Archaeology, 1991), 168-169, fig. 69.356, pl. 16.B.

³⁹⁴ J. M. Coles and F. W. Hibbert, "A Neolithic Wooden Mallet from the Somerset Levels," *Antiquity* 46 (1972): pl. 11; M. Taylor, "The Wood," in *The Flag Fen Basin: Archaeology and Environment of a Fenland Landscape*, ed. Francis Pryor (Swindon: English Heritage, 2001), 222, no. Wood B3249, figs 7.58 and 7.59.

more extant. Stone and wooden hammers were probably more commonly used.³⁹⁵ Karimali states that, along with many other tools, stone hammers for most tasks were not widely replaced with metal hammers until as recently as the pre-industrial era because of stone's cheapness and its suitability for hammering.³⁹⁶

Whether or not Minoan metalworking hammers had handles is a significant issue. Branigan assumes that stone metalworking hammers in the Aegean must have been shaft-hole hammers mounted on wooden handles.³⁹⁷ However, other than some apparently ceremonial hammers, Minoan hammers for utilitarian purposes rarely have shaft-holes for handles.³⁹⁸ This begs the question why, when other hafted tools were available, hafted stone hammers were so uncommon. It cannot have been because of ignorance, and must have been for a technical reason. For the tasks undertaken by Minoan smiths, perhaps unhafted hammers were more useful. They were certainly readily available and did not require any preparation.

Ogden says that there is no evidence for the use of hafted hammers for metalworking in antiquity before the middle of the 1st millennium BC.³⁹⁹ Unhafted hammers have been used for metalworking in several other cultures. This is illustrated in the metalworking scenes in the Tomb of Rekhmire (**figure 143**). Forbes says that hafted hammers were unknown in Egyptian metalworking until the Iron Age.⁴⁰⁰ Sixteenth-century Inca and Colombian smiths also used unhafted hammers (**figure 114**).⁴⁰¹ It is possible that some stones may have been lashed to handles, though the forms which are large enough, cobbles and pestles, have shapes that are not suitable for this. Stones with grooves for handle lashing, found in other parts of the Aegean, have apparently not been found in Crete.

Pestle forms are apparently appropriate for working sheet metal.⁴⁰² Garcillaso de la Vega observed Inca goldsmiths using pestle-form, or elongated hammers for hammering concave forms and Ogden suggests that a small haematite pestle from Ur

³⁹⁵ Branigan, *AM*, 85; Evely, *Minoan Crafts* 1, 108.

³⁹⁶ L. Karimali, "Lithic Technologies and Use," in *The Archaeology of Mediterranean Prehistory*, ed. Emma Blake and A. Bernard Knapp (Malden: Blackwell Publishing Ltd., 2005), 203, 205; L. Karimali, "Lithic and Metal Tools in the Bronze Age Aegean: A Parallel Relationship," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008).

³⁹⁷ Branigan, *AM*, 85, 67, fig. 2.

³⁹⁸ Evely, *Minoan Crafts* 1, 97; Shaw, *Minoan Architecture: Materials and Techniques*, 54-55.

³⁹⁹ Ogden, *Jewellery of the Ancient World*, 34.

⁴⁰⁰ Forbes, *Studies in Ancient Technology* 8, 131-132.

⁴⁰¹ Vega, *Royal Commentaries*, 130-131; G. Benzoni, *History of the New World by Girolamo Benzoni, of Milan, Shewing his Travels in America from A.D. 1541 to 1556: With Some Particulars of the Island of Canary*, trans. W. H. Smyth (London: Hakluyt Society, 1857), 251.

⁴⁰² Ogden, *Jewellery of the Ancient World*, 35.

was probably used for forging gold foil.⁴⁰³ Egyptian depictions of vessel-making seem to show smiths using spherical cobblestone held in the hand (figure 143, bottom left and bottom right). Vega says that the Inca smiths used hammers of this shape for heavy work, though he does not specify what tasks were undertaken with them.⁴⁰⁴

Organic materials, wood and bone or horn, are possibilities for Minoan metalworking hammers. Wood and horn hammer-heads are sometimes used by modern metalsmiths for raising, usually where the material is quite thin and elongation of the wall during raising is not desired. An experiment in sinking and raising with a sheep's shank bone is illustrated by Knauth, and proved very successful on silver sheet.⁴⁰⁵ However, wooden artefacts have not survived in Crete and no bone or horn artefacts that I am aware of have been identified as having been used for hammering.⁴⁰⁶

The evidence presented here indicates that neither bronze hammers nor hafted stone hammers were common for metalworking processes. The typical hammering tools found within metallurgical contexts are simple stone forms – either unmodified cobblestones and pestles or deliberately-shaped pestles. The use of shaft-hole hammers and bronze hammers cannot be ruled out completely, however, and were perhaps just uncommon. Wooden hammers must have been used, but it is impossible to determine what forms these took.

§4.4.2. Hammering Surfaces: Anvils, Stakes and Hollows

Stakes and Anvils

It can be difficult to determine the difference between an anvil and a stake. A simple distinction is that forging is carried out on an anvil whereas raising is carried out on a stake. That is, metal is hammered on an anvil, and hammered over a stake. In many cases, a single piece of equipment might be used for either process. For the sake of simplicity, I have listed anvils here as flat, slab-like objects for basic forging purposes, as it is not possible to raise metal over a flat surface. Objects which can be hammered over are listed as stakes.

Stone slabs identified as possible anvils have been recovered at Kommos (§5.4), from the Artisans' Quarter at Mochlos (5.8.1), and at Poros-Katsambas (§5.10). Of

⁴⁰³ Vega, *Royal Commentaries*, 130-131; Ogden, *Jewellery of the Ancient World*, 35, fig. 4.3.

⁴⁰⁴ Vega, *Royal Commentaries*, 130-131.

⁴⁰⁵ Knauth, *The Metalsmiths*, 74-75.

⁴⁰⁶ Evelyn, *Minoan Crafts* 1, 97.

these, one in House X at Kommos and that at Poros-Katsambas are unpublished. Those which have been published vary in form.

†Sandy limestone anvil/mould (**figure 144**).⁴⁰⁷ Dimensions unknown. Flat slab with three circular depressions. Kommos, House with the Snake Tube, LM IIIB (§5.4.3). Three other similar objects were found in other Kommos houses, two of those in the vicinity of metallurgical evidence. Blitzer identifies them as anvils and/or moulds, with the depressions being used for casting billets. They seem unlikely moulds, as their weight would make them difficult to manoeuvre into a hearth for pre-heating. McEnroe suggests they may be pot stands.⁴⁰⁸ Below, I identify them as potential sinking hollows.

†Fine-grained black crystalline limestone anvil (**figure 145**).⁴⁰⁹ Broken, originally rectangular, 484 x 387 x 26 mm. 9.1 kg. Flat upper surface polished flat with many marks from percussion and abrasion. Mochlos, Artisans' Quarter, Building A, final LM IB (§5.8.1). Another slab from the same period which was also identified as an anvil was found in the same building. Because the slab is only thin, this anvil would be suitable for forging only small items. Heavy hammering would more than likely break it.

Stone slabs appear to have been used as anvils in Egypt, as depicted in the scenes from Rekhmire's tomb (figure 143, bottom right). Inca and Colombian smiths used stone anvils (figure 114).⁴¹⁰ Blocks of hardwood might also serve as anvils when major stretching is not required. These also have the advantage of being easily shaped for specific tasks.

Several bronze artefacts have been proposed as stakes for metalsmithing. None come from confirmed metallurgical contexts.

Bronze hammer/T-stake (figure 130).⁴¹¹ Dimensions 106 x 16 mm. Circular handle cast in one piece with head 20 mm in diameter, total

⁴⁰⁷ Blitzer, "Minoan Implements and Industries," 485-486, no. GS 705, pl. 8.59C.

⁴⁰⁸ J. McEnroe, "The Late Minoan Period," in *Kommos I: Part 2*, ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 1996), 230.

⁴⁰⁹ T. Carter, "The Stone Implements," in *Mochlos IC*, ed. Jeffrey S. Soles and Costis Davaras (Philadelphia: INSTAP Academic Press, 2004), 75, no. IC.410, pl. 23, IC.410.

⁴¹⁰ Vega, *Royal Commentaries*, 130; Benzoni, *History of the New World*, 251.

⁴¹¹ HM 1795; Deshayes, *Les Outils* 1, 298, no. 2321, pls 40.3, 63.1; Catling, *CBMW*, 100; Evelyn, *Minoan Crafts* 1, 101, no. 3, fig. 44.3, pl. 22.3.

height 133 mm. One face is ovoid and domed, the other flat and octagonal to circular in section. Weight 650 g. Samba Pediados, date unknown. This object has been proposed as a stake by Catling, and as a hammer by Deshayes.⁴¹² It is possible that it was used for both purposes. It is not uncommon for modern metalsmiths to use hammers as stakes and vice versa. As a stake, the object provides several different working surfaces over which metal might be hammered. It might be more suitable as a stake than a hammer because of the weight of its 'handle', as discussed in §4.4.1 above.

Bronze s-stake (**figure 146**).⁴¹³ Long s-shaped shaft 502 mm long and 22-28 thick with two heads, one flattened into a wedge 35 mm wide, the other ovoid, 40 x 46 mm, with a curved face. The shaft has a collar roughly one-third along its length. Ayia Triada, ?LM I. This object is similar to stakes depicted in vessel-making scenes from the Rekhmire tomb (**figure 147**). Neither of its faces is ideal for raising over, but it could be useful for localised shaping. Hundt suggests that it would be ideal as a snarling iron. However, since vessels requiring this method are virtually unknown in the Minoan corpus, the stake may be an import, perhaps from Egypt, and certainly does not represent common Minoan vessel-making equipment.

Bronze anvil/stake (**figure 148**).⁴¹⁴ Dimensions 115 x 40 mm. Rectangular block, slightly curved. One bottom corner is rounded, the other curves to a ridge. Top edge has a curved face 40 x 48 mm. Zakros Palace West Wing, LM IB. Platon describes the object as an anvil. Hundt believes that it was used as a stake for making large bronze vessels. The shape makes it suitable for the basic raising seen on Minoan vessels, since it is short and does not have the length required for creating closed forms. Its main working surface is slightly domed with well-defined edges which could be suitable for raising over. The ridge at

⁴¹² Catling, *CBMW*, 100; Deshayes, *Les Outils* 1, 122.

⁴¹³ Deshayes, *Les Outils* 1, 122, pl. 63.4; H. J. Hundt, "Zwei minoische Bronzegeräte zum Treiben von Metallgefässen aus Kreta," *ArchKorrBl* 16, no. 3 (1986): 281; Evelyn, *Minoan Crafts* 1, 101, no. 23, pl. 22.23.

⁴¹⁴ HM 2621; N. Platon, *Zakros: The Discovery of a Lost Palace of Ancient Crete* (New York: Scribner, 1971), 129, 124, bottom right; Hundt, "Zwei minoische Bronzegeräte zum Treiben von Metallgefässen aus Kreta," 281, fig. 1.1; Evelyn, *Minoan Crafts* 1, 101, no. 25.

the bottom end might also be good for raising over. Its slightly curved shaft would help to position the upper working surface in difficult to reach parts of a vessel.

It is possible that stones were used as stakes, but none have been identified as such. They would probably be difficult to distinguish from other percussion tools. Because a raising stake must project horizontally, it is difficult to imagine how a stone stake might be secured for working on. If it is very securely bound to a post by some method, it may be feasible to raise over it. It is more than likely that wood was the usual material for stakes. Because stakes must have a specific profile and cross-section, wood is an ideal material, since it is readily shaped and can be re-shaped as required over the course of the process.

The manner in which stakes are secured plays an important role in determining their design. There is no evidence of this from Crete, and without knowing for certain what form stakes took, it is impossible to draw any conclusions. Three possibilities come from Egyptian sources. In the Rekhmire scenes, an s-stake similar to the one discussed above appears to be leaning against a timber support, more than likely using the collar on the shaft to hold it in place (figure 147). This system would of course only work with this type of stake, and one wonders how stable this would be for heavy hammering. In his reconstruction of the raising of an Egyptian silver bowl, Johnson props one end of a long, cylindrical wooden stake on a timber support and secures the other end underneath a wooden stump.⁴¹⁵ The support is made from two vertical pieces fixed to a horizontal base. The upper end of the stake sits between the two uprights (figure 149). A third method is depicted in an Old Kingdom image from Unas, showing the stake tied to a post (figure 150).

Sinking Hollows

Any hollow depression can be used for sinking. No artefact can be definitively categorised as a sinking hollow. One possibility is described here.

†Sandy limestone slab with hollows (figure 151).⁴¹⁶ Dimensions unknown. Two depressions in surface. Kommos, House with the Press, LM IIIB (§5.4.4). Blitzer proposes that this and two others in Kommos houses are anvils or moulds. The deeper of the two hollows appears to

⁴¹⁵ Johnson, "An Experiment in Ancient Egyptian Silver Vessel Manufacture," fig. 4.

⁴¹⁶ Blitzer, "Minoan Implements and Industries," 486, no. GS 703, pl. 8.59D.

be suitable for sinking. If the slab was used as an anvil, it might also have been used for sinking.

Minoan smiths probably used wood with hollows carved out with chisels as are used today. Wood is certainly more versatile for this than stone, since hollows can easily be adapted as required.

Hammering Surfaces: Summary

The archaeological evidence of the surfaces on which vessels were worked presented here suggests that, as for hammers, bronze tools of this type were rare. As was discussed above in §4.4.1, if bronze stakes or anvils had been common, even accounting for the possibility that many were recycled, we should still expect to see more remaining. Bronze stakes may have been used in some workshops, but the lack of remains suggests that wood was much more common. Anvils were probably stone, and perhaps in some cases wood. Sinking hollows may have been carved in stone, but wood is once again most likely.

The lack of bronze stakes may account for the open forms typical of the Minoan vessel tradition (see §1.4). A wooden stake would have limited functionality as a stake for producing narrow-mouthed vessels because the stake must be curved and long and narrow enough to fit through the opening. Such a thin wooden stake is unlikely to be strong enough to withstand the heavy hammer blows required to raise a vessel. The stake would bounce, preventing accurate hammering, and would break quickly.

§4.4.3. Joined Appendages: Rims, Handles and Spouts

The final hammering stages on a vessel may involve work on rims, handles and spouts. Rims were often caulked to thicken the rim and stabilise the vessel's walls. For slight thickening, after each of the last two to five shaping rounds, the rim is caulked by forging it down and back into the wall. Heavily worked rims, such as those where the rim overlaps the vessel wall, may be caulked after all or most rounds throughout the forming of the vessel (**figure 152**). In some cases, rather than being caulked, the rim was left thin and either folded or rolled outwards and around a core of lead or copper wire. Folded rims were generally folded outwards, but in some cases they folded out and in again. Folded rims are made simply by tapping the rim over the sharp edge of a working surface such as a stump or anvil (**figure 153**). For rolled rims, the rim was probably folded out first, the wire set in place and the rest of the rim gently forged

around it (**figure 154**). Rolled rims which do not have a core may have been rolled over some material which has not survived.

Handles and spouts which extend from the body of the vessel are at this stage hammered out from material allocated for the purpose on the rim. For a handle, the original billet probably had a rod protruding from the rim. This could now be forged out to the desired cross-section and bent into the required curve. Short spouts may only require a thickened section to be allocated for them on the rim; provisions for long spouts may be protrusions similar to those for handles. These would be forged out to the desired length and thickness on the anvil and carefully sunk into a groove, probably carved in stone or wood.

§4.5. Finishing Processes

§4.5.1. Planishing

The initial stage of finishing in modern vessel-making is planishing. General planishing can be performed roughly over the surface, with the vessel on a stake.

This evens out major defects in the vessel's profile. The hammer can be of a soft material such as wood or rawhide, and the stake can be of metal or timber.

Alternatively, this general planishing can be performed on the inner surface of the vessel if it is accessible, using a sinking hollow or a flat stump-top as the hammering surface. More precise planishing, where the entire surface is meticulously lightly forged, producing a faceted surface, requires a metal stake which conforms perfectly to the inner profile of the vessel, and a very smooth-faced metal hammer.

The evidence discussed above in §4.4 above suggests that equipment for the latter technique was not available and therefore, it is unlikely that Minoan vessels were planished in the manner common today. No images of Minoan vessels show the faceted surface characteristic of planishing. One might argue that the facets were removed with abrasives, but we should expect to see some evidence, since planishing also leaves distinctive marks on the inner-surface of the vessel. General planishing, however, may have been carried out. The equipment was available, and it is a simple method for consolidating the profile and hardening the material.

§4.5.2. Finishing and Polishing

Metal files, the most common tool for surface cutting in modern metalsmithing, were not used by Minoan smiths. Apart from the fact that none exist in the archaeological record, their use is practically unknown in antiquity other than for working wood in Egypt.⁴¹⁷ Any filing which was required must have been carried out with coarse abrasives followed by successively finer abrasives to produce a polish.

There is a range of forms of abrasive stone tools found in Minoan contexts. Evely categorises these according to their apparent use into polishers and whetstones, but points out that it is difficult to distinguish between the two.⁴¹⁸ Both are identifiable by the presence of flattened surfaces which are sometimes polished, and come in a range of shapes – square, triangular and amorphous. Frequently these tools show signs of percussive damage and it is likely that one tool was used for both processes. Pieces of pumice showing signs of abrasion are also prevalent at Minoan sites.

Abrasive tools would have been used in several crafts – metalwork, stone working, textile production (for preparing dyestuff) – and for domestic tool maintenance. The prevalence of whetstones in Minoan houses indicates that some households kept them for sharpening metal tools rather than relying on specialists. It is difficult to link any specific artefacts with specific tasks.

As far as these tools are concerned with metalworking, they may be labelled finishing tools. I will not venture to link specific artefacts with metalworking, since this is not possible, but will simply describe the types of artefacts which would be appropriate for metalworking tasks. These tasks include cutting metal surfaces to remove scratches and create a polish, and sharpening tools after their manufacture. The only requirement for such tools is that they have abrasive qualities. For coarse cutting, appropriate stone tools which are commonly found are of emery, limestone, marble, siltstone and sandstone, while slightly less common tool materials include quartzite.⁴¹⁹

†Marble whetstone/polisher (**figure 155**).⁴²⁰ Dimensions 46 x 20 x 14 mm, weight 20 g. Rectangular block with all corners flattened by abrasion. Knossos, Unexplored Mansion, LM II (§5.2). The flatness of the facets indicates that this tool was used to cut flat surfaces.

⁴¹⁷ Forbes, *Studies in Ancient Technology* 8, 133; Ogden, *Jewellery of the Ancient World*, 86.

⁴¹⁸ Evely, "The Other Finds," 224, 226; Evely, *Minoan Crafts* 1, 111-112.

⁴¹⁹ Evely, *Minoan Crafts* 1, 111.

⁴²⁰ Popham, *The Minoan Unexplored Mansion at Knossos*, 45, no. L 18, pls 208.5 and 227.14; Evely, "The Other Finds," 224-225.

†Quartzite polisher (**figure 156**).⁴²¹ Dimensions 91 x 45 x 4 mm, weight 250 g. Amorphous with rounded edges, one flattened face with high polish and roughened ends. Unexplored Mansion, ?LM II (§5.2). Evelyn classes this as a polisher and grinder-pounder. The roughened ends indicate that it was used for pounding and well as finishing. The size and weight of this tool would make it appropriate for hammering as well as finishing.

†Emery finishing tool (**figure 157**).⁴²² Dimensions approximately 58 x 43 x 53 mm, weight 300 g. Rounded shape made trapezoidal from abrasion and with signs of percussion. Kommos, House with the Snake Tube, LM IIIA2-B (§5.4.3). This tool appears to have been used for hammering and finishing.

Ogden lists several substances which may have been used in antiquity for producing a high polish, many of which are mentioned by authors such as Pliny the Elder and Theophilus and in the Leyden X papyrus: pottery, clay, chalk, marble, limestone, pumice, charcoal, ashes and sand.⁴²³ Most of these were available to the Minoans, and slate and pumice finishing tools have been found. Pumice in particular has been found in abundance in Crete, originating from Cycladic volcanoes,⁴²⁴ and appears to have been widely-used as an abrasive. Pumice tools have been found amongst metallurgical materials at the Unexplored Mansion (§5.2), the Kommos southern harbour complex (§5.3), the Mochlos settlements (§5.7.3) and Artisans' Quarters (§5.8.1) and at Poros-Katsambas (§5.10.2). Wear-patterns from use include faceting and grooves. No charcoal showing signs of such use has been reported that I am aware of, though these might well go unnoticed during excavation.

Finishing tools may have been used with lubricants. Water or oil are suitable. Evelyn also suggests grease and vegetable juice.⁴²⁵ Abrasive powders such as pumice or emery may also have been used, applied by hand or with a piece of wood or leather.

Burnishing might also have been used for producing a high polish. Burnishing tools, which compress material rather than cutting it, should ideally be as hard as or harder than the material on which they are used. For this reason, they may not be identifiable,

⁴²¹ Popham, *The Minoan Unexplored Mansion at Knossos*, 67, no. M 198, pls 208.8, 227.6; Evelyn, "The Other Finds," 224, no. M 198.

⁴²² Blitzer, "Minoan Implements and Industries," 447, no. GS 302, pl. 8.71B.

⁴²³ Ogden, *Jewellery of the Ancient World*, 86-87.

⁴²⁴ Evelyn, *Minoan Crafts* 1, 112.

⁴²⁵ *Ibid.*, 111.

as they may not show signs of wear unless they have been used extensively. Types of stone which were used to make seal stones in Crete and which are suitable include haematite, chalcedony and agate. These tools should be smooth, ideally polished, and a shape and size suitable for manipulating with the fingers.

§4.6. Further Working

At this stage, a one-piece vessel has been hammered into shape and brought to a polish. Some vessel types, such as simple bowls, are now finished. Most, however, still require more work for rims, legs and handles. Vessels made from two or more sections require more construction to complete the body before appendages can be added.

§4.6.1. Separate Appendages: Legs, Handles and Rims

Separate legs, handles and some rims were probably cast by lost-wax casting, though in some cases handles and legs were forged from cast billets.⁴²⁶ Matthäus reasons that they must have been cast by lost-wax since there are no surviving moulds for such objects (at the time of the publication of *BKMK*); lost-wax moulds are destroyed during use, so are rarely found. It would be more difficult to hammer the profile of a vessel to fit the attachment-plate of a pre-made handle or leg than it would be to make a wax attachment-plate fit a finished vessel body. For this reason, it is unlikely that these were cast in permanent moulds such as open or bivalve stone moulds since these would allow only one size and shape of appendage to be made repeatedly. In addition, since it is easier to fit an appendage to the hammered form, handles, legs and rims would have been made after the vessel had been hammered.

Probable examples of lost-wax moulds for vessel handles have since been recovered from Final LM IB Mochlos in the Artisans' Quarter (§5.8.1) and LM IIIA2 or LM IIIB Palaikastro.

†Lost-wax mould fragments for possible cauldron handle (figures 158 and 159).⁴²⁷ Matrix for a double-annular ring-handle with attachment plate for a cauldron. Fine inner lining and coarse exterior envelope. Palaikastro, LM IIIA2 or LM IIIB (§5.9).

⁴²⁶ Matthäus, *BKMK*, 329, 331; Popham, Catling, and Catling, "Sellopoulo," 233.

⁴²⁷ S. Hemingway, "Minoan Metalworking in the Postpalatial Period: A Deposit of Metallurgical Debris from Palaikastro," *BSA* 91 (1996): 230, 238-239, nos 91/3445a, b and c, figs 6.8, 6.9, 11.4, 11.5, pl. 40.a.

§4.6.2. Joins

Riveting was the standard method for joining vessel sections and connecting appendages to the vessel body. A small number of items may have been soldered together.

Hole-Making

Before rivets can be put in place, holes must be made in the metal. Holes can be created in two ways, by piercing or by drilling. Punching displaces material whereas drilling removes it. Piercing is as simple as driving a sharp punch through the material with a hammer. The item can be supported on a soft backing such as wood. This method tears through the material and, in sheet, leaves a funnel-shaped hole and rupture prongs which must then be cleaned up for further work to take place. The surrounding material may also be warped by the punching action.

A method for punching through sheet described by Rostoker involves first punching into the sheet from one side only deep enough to create a dimple.⁴²⁸ From the second side this is hammered flat and then punched through again. This alternating between sides is repeated until a small hole is formed which is then expanded with a long tapered tool called a drift. The advantage of this technique is that the hole is round and neat, leaving surrounding material reasonably flat. Rostoker says that it is effective for producing many holes very close to one another or to the edge of a sheet and that the technique is quite quick. The simple punch-through method first described above is only suitable for quite thin material such as sheet. Rostoker's method may perhaps be used on thicker material.

Bronze awls have been found in fair numbers on Crete, and a small number from metallurgical sites.⁴²⁹ They consist of a rod of metal with a sharp-pointed end. Some listed by Evelyn have a tang for a handle and may be forged to a taper with a square section. This design would help for enlarging punched holes by twisting the tool within the hole.

A drilled hole is round and neat and leaves the surrounding material flat. Some Minoan bronze drills are extant, but are probably for stone-working or carpentry.⁴³⁰ It is unlikely that smiths were able to drill through metal during the Bronze Age, since there was no material available which was hard enough to cut through it. Bronze is not

⁴²⁸ W. Rostoker, "Ancient Techniques for Making Holes in Metal Sheet," *AJA* 90, no. 1 (1986).

⁴²⁹ Evelyn, *Minoan Crafts* 1, 88-92.

⁴³⁰ *Ibid.*, 78.

hard enough to cut bronze or even softer metals such as gold, and sharp tools made from flint or obsidian do not work because they are too brittle.⁴³¹

Riveting

Rivets would have been made from a narrow length cut from a billet or cast rod with a chisel. Mushroom-head rivets were probably cast either by the lost wax method or with a two-piece mould, though they could also have been forged from rod. A swage block could have been used to shape rivet shanks and heads. A swage block is a type of anvil with channels along its surfaces in which rod can be forged to change the shape of its cross-section and, today, have holes of various sizes which can be used to support a piece of rod while an end is being forged. One Minoan stone swage block is extant.

Stone swage block (figure 160).⁴³² Dimensions 40-50 x 25 mm. One face has two channels, approximately 10 and 5 mm in diameter. The opposite face has a single channel approximately 15 mm in diameter. One end has a T-shaped recess 20 x 12 mm. Palaikastro Block ξ, ?LM. Dawkins describes the object as a mould. Evelyn's suggestion that it is a swage block is more likely. Evelyn also proposes that it may have had a top half and that the T-shaped recess may have been a mould of some kind.

As in the case of anvils, swages could also have been made from wood. Bronze is also a possibility, though none are extant.

For the simpler rivet applications such as joining raised sections of vessels, closing the rivets is a simple matter of forging the ends flat. Before the rivet is placed in the hole, one end is forged flat. When the head has a satisfactory diameter, the rivet is placed through the holes in the metal item with the already-flattened head on the side of the item which is more difficult to work on. The first head is supported on an anvil or stake to provide resistance against which to forge the second head flat. Evelyn also suggests the use of punches to close rivet heads.⁴³³

⁴³¹ Ogden, *Jewellery of the Ancient World*, 44; Hoffman and Davidson, *Greek Gold: Jewelry from the Age of Alexander*, 34. Ogden and Hoffman and Davidson are referring to tools for engraving, another process which requires cutting metal.

⁴³² R. C. Bosanquet and R. M. Dawkins, *The Unpublished Objects from the Palaikastro Excavations 1902-1906*, BSA Suppl. 1 (Athens: British School of Archaeology at Athens, 1923), 124, fig. 105; Evelyn, *Minoan Crafts* 2, 365-366, fig. 144.4.

⁴³³ Evelyn, *Minoan Crafts* 2, 368.

Hot-Joining

There is some evidence to suggest that, on rare occasions, bronze or copper vessels were soldered together. Matthäus suspects this is the case for a lekane with a separate base from Sellopoulo and Marinatos observed that a one-handled basin from Malia appeared to have its rim attached with a tin-lead solder.⁴³⁴ There are, however, no tested examples of soldering or hot-joining of copper or bronze from Crete. A number of precious metal vases from mainland Greece which Davis lists as being of Minoan manufacture seem to include hot-joining methods in their construction.⁴³⁵

Hot-joining in antiquity is a topic which has been covered extensively.⁴³⁶ Nevertheless, there still seems to be a fair amount of confusion. The differences between the various methods are distinct and significant. It is important to be specific about exactly which joining methods and materials are being referred to, especially when describing artefacts, as each method requires different knowledge and technology. The hot-joining methods discussed here are colloidal hard soldering, hard soldering, soft soldering, brazing and running on.

Colloidal hard soldering, used extensively in antiquity, is very likely to have been used by Minoan smiths for joining high-carat gold and high-percentage silvers. The alternative for these applications, hard soldering, apparently was not used, since solder is not visible on gold and silver Minoan work.⁴³⁷ Colloidal hard soldering was probably used to join the components of the wasp pendant from Malia. It is only possible on high-percentage gold and silver alloys, however, so it is not useful for copper alloy vessels. It may have been used on precious metal vases as well as jewellery.

Hard soldering uses solders which melt above 550°C.⁴³⁸ Gold is usually soldered with a gold/silver alloy or a gold/copper alloy, both of which were apparently used for gold items from the Royal Tombs at Ur, including a spouted cup.⁴³⁹ Today, silver is soldered with a silver/copper alloy, but Tylecote says that this was rarely used before

⁴³⁴ Matthäus, *BKMK*, 328; S. Marinatos, "Le chernibon homérique dans la civilisation créto-mycénienne" *BCH* 53 (1929): 373.

⁴³⁵ Davis, *AGSW*, 344-345.

⁴³⁶ Maryon, "Metalworking in the Ancient World," 102-106; Ogden, *Jewellery of the Ancient World*, 58-70; Evely, *Minoan Crafts* 2, 386-387, 410-411.

⁴³⁷ J. Wolters, "The Ancient Craft of Granulation: A Re-Assessment of Established Concepts," *Gold Bulletin* 14 (1981): 122.

⁴³⁸ Forbes, *Studies in Ancient Technology* 8, 138.

⁴³⁹ *Ibid.*, 138; Ogden, *Jewellery of the Ancient World*, 64; P. Collins, "The Tomb of Puabi," in *Art of the First Cities: The Third Millennium B.C. from the Mediterranean to the Indus*, ed. Joan Aruz and Ronald Wallenfels (New York: Metropolitan Museum of Art, 2003), 116-117, no. 67a.

the eleventh century AD.⁴⁴⁰ Copper alloys can be hard-soldered with silver/copper alloys, which was used in Egypt as early as the Old Kingdom. Furniture from the Fourth Dynasty Tomb of Hetepheres was assembled with this technique.⁴⁴¹ A hole in an Eighteenth Dynasty bronze bowl was repaired with silver solder.⁴⁴² This contemporary evidence suggests that hard soldering of copper alloys may have been known to the Minoans, though it could not have been common. Precious metal vessels might have been joined with this method.

Soft soldering uses a tin-lead alloy as a solder with a melting temperature between 185 and 300°C.⁴⁴³ It is suitable for joining copper alloys, although the bond created is not as strong as with hard soldering. Soft soldering did not become common until the Classical period, and was commonly used on Roman silverware and lead pipes.⁴⁴⁴ Examples of soft soldering come from mid-fourth century BC Mesopotamia and Old Kingdom (mid-third century) Egypt.⁴⁴⁵ If Marinatos' observation concerning the one-handled basin from Malia is correct, soft soldering would have been the method used there. Soft soldering may have been used on precious metal vessels, though it is generally regarded as an inferior method for joining precious metals due to the weakness of the join.

The term brazing is frequently used interchangeably with soldering. However, brazing refers to instances where a copper alloy is used as a solder, usually brass, an alloy of copper and zinc. I can find no evidence of brazing in antiquity. Ogden says the use of copper/zinc brazing alloys in antiquity has not been proven.⁴⁴⁶

Running on, or burning, describes the connecting of components by pouring molten metal over the join. There are no examples of this technique from the Bronze Age Aegean that I am aware of. The Egyptians were apparently familiar with the technique by the Nineteenth Dynasty (late second millennium BC), as is exemplified by a repair of a hole in a bronze bowl.⁴⁴⁷ Running on would not be suitable for joining vessel sections owing to the difficulty of pouring molten metal between the overlapping layers, and the

⁴⁴⁰ R. F. Tylecote, *The Early History of Metallurgy in Europe* (London: Longman, 1987), 241.

⁴⁴¹ Ogden, *Jewellery of the Ancient World*, 67.

⁴⁴² H. E. Winlock, "An Egyptian Flower Bowl," *MMS* 5, no. 2 (1936): 150, fig. 5.

⁴⁴³ Ogden, *Jewellery of the Ancient World*, 67.

⁴⁴⁴ Forbes, *Studies in Ancient Technology* 8, 137; Tylecote, *The Early History of Metallurgy in Europe*, 240-241.

⁴⁴⁵ Forbes, *Studies in Ancient Technology* 8, 137; Ogden, *Jewellery of the Ancient World*, 67.

⁴⁴⁶ Ogden, *Jewellery of the Ancient World*, 67.

⁴⁴⁷ Radwan, *Die Kupfer- und Bronzegefäße Ägyptens: Von den Anfängen bis zum Beginn der Spätzeit*, 99, no. 273, pl. 50.273.

likelihood that the molten metal would warp the thin walls of the vessel. It is far more suitable for butt joints.

It appears that the only methods of hot joining copper alloys which may have been known to Minoan smiths and used on vessels are soft soldering, for which there is one possible example, and hard soldering, for which there are no examples. For precious metals, both of these methods as well as colloidal hard soldering may have been used. Analyses of the vessels concerned would be very helpful. It appears that, although soldering was known, it was uncommon for vessel-making. Rivets were the norm.

§4.6.3. Cutting

After vessels or vessel sections had been hammered, some parts might need to be cut. Middle sections of hydrias, for example, would need their bases cut out either during or after hammering. Other components might also require cutting at some stage: for example, cutting pieces off billets and cutting rods for rivets. The main method available would have been with chisel and hammer. Less precise methods would be bending thin material such as sheet or wire back and forth until it cracks or forging thicker material against a sharp corner on an anvil.

Minoan chisels came in several different shapes and sizes. Evely has created an extensive typology.⁴⁴⁸ The types include those which were used with a hammer, indicated by a damaged butt, and those which must have been worked by hand, with undamaged butts. The cutting ends are straight or curved and flared (**figure 161**). For breaking up metal and cutting rod and sheet, the chisel would ideally be relatively stout and sharp since long narrow chisels would have a tendency to bend when struck with a hammer. The working ends of most small chisels are unidentifiable due to corrosion. Chisels have been found at many Minoan metallurgical sites, but whether these were equipment or products is often unknown. Several sites also had moulds for producing chisels.

We have now examined Minoan metallurgical equipment which relates to the vessel-making process. Substantial parts of the process have been illuminated. After sourcing the metal in the form of billets or scrap, the smith would have broken down larger pieces and cast them in open or bivalve moulds or by the lost-wax process, alloying the

⁴⁴⁸ Evely, *Minoan Crafts* 1, 2-19.

material as required. The billet was probably annealed on an open hearth with a blowpipe for draught, and hammering was probably carried out with stone and timber hammers on stone and timber anvils and stakes. Bronze hammers and anvils may have been used by some smiths, but they were apparently uncommon. After achieving the vessel form, the smith finished the vessel with abrasives, usually stones, and may have burnished the vessel's surface. Separate appendages such as handles, rims and legs could be forged, but for the most part were cast by lost-wax. These were attached with rivets, as were separately-made vessel sections. It is possible that some vessel parts were soldered together. Holes were punched rather than drilled, and sheet metal was cut with chisels.

In the following chapter, we will examine the evidence of Minoan metallurgical workshops and installations in order to find any indications of vessel-making taking place at specific sites.

Minoan Metallurgical Sites

Having identified and examined Minoan metallurgical equipment and its role in the vessel-making process, we will now turn to the metallurgical sites themselves and attempt to identify specific sites at which vessel-making took place. There is an abundance of metallurgical evidence in Crete covering the entire Bronze Age. Since this study focuses on vessel-making, the sites discussed here are only those which date to the main periods of vessel manufacture, from the late Protopalatial to Postpalatial periods.

Typically, a site is identified as having metallurgical significance because of evidence from casting: crucibles, moulds and metal dribbles or slags are typical indicators. Unfortunately, it is often evidence from casting alone which can indicate a metallurgical site, because most other metalworking activities leave very ambiguous evidence. The evidence for forging, for example, may be no more than a rock which was used to beat the metal. Because of this, it is likely that metalworking which did not involve casting was carried out at many more sites than we are aware of. In some cases, a single mould or crucible is the only reported evidence of metalworking having taken place at a location, and it is difficult to draw many conclusions from these occurrences other than the fact that casting took place. Therefore, this chapter does not provide a conclusive list of metallurgical sites, but covers those sites which provide enough evidence to draw useful conclusions from and sites which have previously been identified as important centres of metallurgy. These are illustrated on the map in **figure 162**. Evelyn has listed sites with minor finds.⁴⁴⁹

Studies of Minoan metallurgical sites tend to view the evidence rather broadly. The evidence from an entire town or an entire period might be considered all together for a general assessment of metallurgical activities in the area rather than each occurrence being individually assessed. I have attempted here to determine individual metalworking workshops or installations to draw conclusions about specific activities at each location. If two or more houses within a town and at the same level contain metallurgical evidence, they are considered separate installations unless there is strong

⁴⁴⁹ Evelyn, *Minoan Crafts* 2, 341.

evidence to indicate a connection. Previous studies have also sometimes overlooked artefacts which are less obviously connected with metallurgical activities. The importance of hammering and finishing tools must not be overlooked, since these represent processes equally as important to vessel making as to casting. I have attempted to trace tools of these types in the workshops and installations discussed here.

The significance of the terms used to describe a location where craft-work took place has been discussed by Evely.⁴⁵⁰ As he puts it, the problem lies in applying terms which reflect contemporary definitions of a work space. In this chapter, the terms workshop and installation are used, preferring the latter for locations where metalworking was apparently a small-scale activity. However, there is usually not enough evidence to draw conclusions of this kind.

The evidence from each installation is listed by category. Raw materials are metal from which items can be made. This includes ingots or parts thereof, wire, rod and sheet, and scrap which may be melted down. Equipment is any item which might be used to work metal. Waste, for the most part, includes droplets, prills and slag. Finished items include objects which might be considered the products of a metalworking installation. For the most part, however, it is impossible to determine if an item is a product, scrap, a piece of workshop equipment or an entirely unrelated artefact. Likewise, there is no way of determining if some pieces of scrap were raw material or waste product. I have tentatively chosen categories under which to place these items, but interpretation is debatable. Lastly, I have attempted to identify what specific metalworking processes were carried out at each site.

§5.1. Gournia: LM IB (Figure 163)⁴⁵¹

Gournia is a settlement centred around a small palace located on a hillside facing the Bay of Mirabello in north-east Crete. Destruction levels from LM IB provide a small amount of scattered evidence for metalworking in three houses: Ea, Fh and Cg.

§5.1.1. House Ea

raw materials: bronze rods

⁴⁵⁰ D. Evely, "Minoan Craftsmen: Problems of Recognition and Definition," in *Problems in Greek Prehistory*, ed. E. B. French and K. A. Wardle (Bristol: Bristol Classical Press, 1988).

⁴⁵¹ Hawes et al., *Gournia, Vasiliki and Other Prehistoric Sites*, 24, 26 and 32, pl. 2; Evely, *Minoan Crafts* 2, 335-338, fig. 133.

equipment: large repaired stone mould with 13 matrices for chisels and billets; bronze nails or awls

possible activities: open- and/or bivalve-mould casting of tools, forging

§5.1.2. House Fh

equipment: stone moulds for a knife, a narrow blade or nail and a small single axe (votive?); ?stone mould cover

waste: ?slag

possible activities: open- and/or bivalve-mould casting of tools

§5.1.3. House Cg

raw materials: copper ingot fragments, bronze scrap (including folded sheet and a handle)

products: chisel, sickle, fish hook, simulacrum of a double-axe

Cg was thought by the excavators to have been the workshop of a metalworker, but Evelyn proposes that the bronze collection here is more akin to a collection of domestic clutter, pointing out that there is no other metallurgical evidence.

possible activities: probably none

The evidence is too disparate to conclude where exactly metalworking was taking place at Gournia. If Hawes' references to slag are concerned with Fh as Evelyn thinks they might be, then that is one potential focus of work. If stone tools had been published from these houses then we might have a better idea of the activities. Ea and Fh, being quite close to one another, may represent a single operation. Nevertheless, it appears as though Gournia in LM IB probably had at least two metalworking installations producing bronze utilitarian items and perhaps votive items also. These installations, casting in open and bivalve stone moulds, were capable of producing most of the bronze items found in the town – double axes, nails, chisels, daggers, hooks, saws and razors, but there is no evidence that they produced vessels such as the tripod cauldron found here or that they undertook lost-wax casting.

§5.2. Unexplored Mansion at Knossos: LM II (Figure 164)⁴⁵²

The Unexplored Mansion at Knossos is located to the west of the Little Palace at Knossos. The LM II evidence contemporary with the metallurgical remains suggests that the building also contained a shrine and was used for storage. The building was not originally intended to contain a bronze workshop but was adapted for the purpose.⁴⁵³ Because the evidence is scattered it is difficult to pinpoint the focus of activities. Evelyn points out that since most of the metallurgical remains were in fill from the upper storey, it is possible that the work was concentrated on the upper floor, providing better light and ventilation, or that most of the work took place outside the building, perhaps on the western side; the building itself may then have been used for storage.⁴⁵⁴ The evidence which is lacking - ingots, moulds and such - may have been removed on abandonment of the site.⁴⁵⁵

raw materials: scrap bronze including vessel fragments; copper and bronze rods, bars and billets

equipment: crucible fragments, some containing traces of gold, silver and bronze, with diameters averaging 60 to 80 mm across and a small number larger at 120 to 200 mm; possible bellows' nozzle; open terracotta mould for small billets; copper strip possibly used for binding mould halves; bronze brazier, possibly used to carry charcoal; bronze basin possibly for quenching; bronze tools including chisels, drills, awls, punches, tracers and tweezers; scale pans; stone pounders, hammers and whetstones; pumice tools; possible small hearth

waste: bronze spill, bronze offcuts

finished objects: ambiguous – some items listed above as equipment may be products

The evidence from the Unexplored Mansion suggests that a large variety of metalworking processes were carried out. Catling and Catling note that the distinction between scrap and finished object is ambiguous.⁴⁵⁶ This may obscure somewhat the processes involved on the site. Casting of some kind was certainly carried out here, but

⁴⁵² Catling and Catling, "The Bronzes and Metalworking Equipment."; Evelyn, "The Other Finds."; Evelyn, "Minoan Craftsmen."; Evelyn, *Minoan Crafts* 2, 338.

⁴⁵³ Evelyn, *Minoan Crafts* 2, 338.

⁴⁵⁴ Ibid., 338.

⁴⁵⁵ Catling and Catling, "The Bronzes and Metalworking Equipment," 206.

⁴⁵⁶ Ibid., 204.

exactly where is difficult to pinpoint. It is possible that the rods, bars and billets were products of the workshop, since the facilities for making these were available here. According to Catling and Catling, all but one of the rods, bars and billets were cast in open moulds.⁴⁵⁷ The single surviving mould consists of a small flat block of baked terracotta with small rectangular indents on opposing sides capable of producing very small billets 42 x 12 mm and 45 x 8 mm (figure 124).

The pi-shaped clay hearth in Room H, discussed in Chapter Four (§4.2.2), was a suitable size for small crucible-based work, but shows no obvious signs of having been utilised for metalworking, such as metal spill or evidence of very high temperatures.⁴⁵⁸ The item described by Catling and Catling as a bellows' nozzle was probably misidentified (see §4.2.2). Metal spill was found throughout the site, making it difficult to pinpoint heating activities. Catling and Catling suggest that the small chisels may have been used for working waxes, though no lost-wax mould fragments were found here.⁴⁵⁹ The presence of gold, silver and bronze in some of the crucibles indicates that precious metals were worked here as well as bronze.

There is a large variety of stone hammers or pounders. Shapes are triangular, spherical, ovoid, disc- and pestle-shaped, and amorphous. Their sizes range from large enough to be held in an open hand to small enough to be held between the fingers and their weights range up to a kilo but are generally 250 g or so. Stone types are predominantly limestone/marble but also include igneous types, fine-grained sandstones and exotic stone types.⁴⁶⁰ They are variously pockmarked and/or faceted.

The various whetstones and polishers all have a size and shape appropriate for holding between fingers. These are generally fine-grained sedimentaries such as limestone or marble, though igneous tools also exist. Several pieces of pumice show obvious signs of having been used as abrasives. Many are flattened on one or more faces, and some have deep grooves.

As noted above, it is difficult to know whether some of the scrap metal was collected elsewhere to be recycled or whether it represents products of the workshop. Of the vessels, the bronze brazier, according to Catling and Catling, dates from no later than LM IB and may have been used to transport burning fuel, the bronze basin may have

⁴⁵⁷ Ibid., 218.

⁴⁵⁸ Evely, *Minoan Crafts* 2, 341, 338.

⁴⁵⁹ Catling and Catling, "The Bronzes and Metalworking Equipment," 206.

⁴⁶⁰ Evely, "The Other Finds," 225.

been used as a vessel for quenching and the broken bronze laver was scrap to be melted.⁴⁶¹

possible activities: casting of billets, recycling, hammering, precious metal working, finishing, ?lost-wax casting

§5.3. Kommos Southern Harbour Complex: MM III – LM IB (Figures 165 and 166)⁴⁶²

Kommos, a small settlement at the western end of the Mesara Plain on the southern coast of Crete, was a harbour town which probably served the palatial centres at Phaistos and Ayia Triada during the palatial periods. Excavations have revealed a set of buildings known as the harbour complex at the southern end of the settlement and parts of the town itself to the north (see §5.4 below). Metallurgical remains from the southern harbour complex are scattered around Building T. The earliest material is at least as early as MM III but may be earlier still. It is difficult to pinpoint a specific work area for this earliest material due to constraints on the excavation of the area. That metalworking was carried out is demonstrated by crucible fragments found in the south-eastern area of the building. During LM IB, metalworking activities were concentrated in the remains of the North Stoa of the Central Court in Building T.

raw materials: copper ingot fragments; bronze bars, rods, wire, sheet and strips

equipment: crucibles with average diameters of 250 to 300 mm, some containing slag and copper prills; tuyères; stone hammers and whetstones; a chisel; pumice tools; a possible quenching container; charcoal fuel; clay for crucible, mould or hearth construction

waste: slag, droplets

At least one of the ingot fragments, probably from slab or bun ingots, may be contemporary with the Building T installation.⁴⁶³ The charcoal found coated the floor

⁴⁶¹ Catling and Catling, "The Bronzes and Metalworking Equipment," 205-207.

⁴⁶² Blitzer, "Minoan Implements and Industries.," J. W. Shaw, "Metals and Metalworking," in *Kommos V*, ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 2006); J. W. Shaw, "Domestic Economy and Site Development," in *Kommos I: Part 2* ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 1996).

⁴⁶³ Blitzer, "Minoan Implements and Industries," 527.

of the work area in the North Stoa where the LM IB crucible fragments were also found, perhaps scattered from the remains of a hearth or kept as fuel.

Some of the crucibles seem to have been used multiple times, a layer of clay having been painted around the inside and outside of the bowl between melts. The two tuyères, with internal diameters of 35 to 90 mm, are suitable for sustaining high temperatures in the large hearth that these crucibles would have required. A larnax, sunk into the ground in the North Stoa near the crucible fragments, is proposed by Blitzer to have been used as a quenching container.⁴⁶⁴

This workshop was capable of producing the various fish hooks, awls, nails, tweezers and so on found in Kommos during this period. The large size of the crucibles indicates that large items were cast here. The presence of whetstones and pumice pieces suggests that bladed equipment was being manufactured, either tools or weapons; knife blades were found in the vicinity. The various pieces of bar and rod suggest tool manufacture; the chisels, forged from rods such as those found here, could be part of the metalworking tool kit, products of the workshop for other crafts or both. Certainly many Minoan metalsmithing processes required chisels, particularly sheet working, and sheet is found here. The stone hammers may have been used for forging any of the large or small tools and weapons. Metal strips and pieces of wire could have been used to bind mould halves, or may have been produced for general domestic needs in the community.

possible activities: casting of large items, forging, chiselling, finishing

§5.4. Kommos Houses (Figure 165)

By LM II, metalsmithing activities in Kommos had moved away from the harbour complex and were scattered amongst several locations around the town itself. These installations were apparently smaller-scale than those in the harbour complex. The five main locations are House X and Building N in the Southern Area, the area around the House with the Snake Tube on the Central Hillside, and in the vicinity of the House with the Press and the North House amongst the Hilltop Houses. The crucibles during this period were much smaller than those of the earlier southern harbour complex installation.

⁴⁶⁴ Ibid., 527.

§5.4.1. House X: LM III⁴⁶⁵

raw materials: bronze bars and wire

equipment: stone mould for earrings, small anvil

finished objects: bronze sickle and knife blades

According to Blitzer, there is evidence of metal working having taken place at House X during LM III.⁴⁶⁶ However, the findings from the excavation are still in the process of being published. Bronze material from House X is mostly of LM III date and includes bars and wire, possibly to be used in a workshop, and a sickle and knife blades which could be products, though there are no signs of bronze casting here. A stone mould for gold or lead earrings and an item which may be a small anvil were found, though these are unpublished and I am not aware of their dates.⁴⁶⁷ The anvil and bronze bars indicate that forging took place.

possible activities: open-mould casting of gold jewellery items; forging

§5.4.2. Building N: LM IIIB⁴⁶⁸

raw materials: copper ingot pieces, copper strips

equipment: possible hearth indicated by a burned floor; stone cobble hammers and whetstones

The material was scattered throughout and to the south of the building. Stone cobbles and whetstones are common tools in many Minoan houses and so may not necessarily have been used for metallurgical processes. The presence of ingot pieces and stone hammers may indicate that forging took place, but the ingot pieces may be from remains of a store. Without any slag, crucibles or moulds, I am reluctant to draw any conclusions about whether or not metal-working activity was carried out here. If there was a hearth here, it is possible that items were being made here with ingot pieces which were broken down and forged, annealed and finished, with no casting. Items

⁴⁶⁵ Ibid; M. K. Dabney, "Jewellery and Seals," in *Kommos I: The Kommos Region and Houses of the Minoan Town. Part 2, The Minoan Hilltop and Hillside Houses*, ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 1996); J. W. Shaw, *Kommos: A Minoan Harbor Town and Greek Sanctuary in Southern Crete* (The American School of Classical Studies at Athens, 2006), 29.

⁴⁶⁶ Blitzer, "Minoan Implements and Industries," 528.

⁴⁶⁷ Dabney, "Jewellery and Seals," 263; Shaw, *Kommos*, 29.

⁴⁶⁸ Blitzer, "Minoan Implements and Industries."; Shaw, "Metals and Metalworking."; Shaw, "Civic Buildings."

which could be made with these processes include wire, nails, needles and simple vessels.

possible activities: forging, finishing, ?annealing

§5.4.3. In the Vicinity of the House with the Snake Tube (Figure 167)⁴⁶⁹

LM IIIA1

equipment: ?clay buff material for making moulds and crucibles

waste: bronze prills

The buff mixture found is the same material as that used to make moulds and crucibles in Kommos. The prills indicate that casting of some kind took place here.

possible activities: casting, ?lost-wax casting

LM IIIA2

raw materials: bronze rod and fragments

equipment: whetstone, hammering stone, crucibles, ?hearth

waste: slag

Casting of some kind probably took place here. The presence of rod and the hammering stone could indicate forging. The whetstone may indicate the production of sharpened tools.

possible activities: casting, annealing, forging, finishing

LM IIIB

raw materials: bronze rod fragments

equipment: chisel, whetstones, emery finishing tool, stone hammering tools, crucibles containing slag and copper prills, lost-wax moulds for double axes, possible stone anvil or mould, possible material for making moulds and crucibles

waste: slag, copper prills

finished objects: chisel, nail

⁴⁶⁹ Shaw, "Hearths and Ovens," 242; Blitzer, "Minoan Implements and Industries."; McEnroe, "The Late Minoan Period."

This LM IIIB evidence comes from three deposits. From the Northeast Room, northeast of the house, come the chisel, rod fragments, nail, whetstone and emery cobble. From the house itself come the stone hammering tools, whetstone, crucible fragments and double axe lost-wax mould. There is also a stone slab from here with three depressions in it which has been identified as an anvil/mould or a pot stand.⁴⁷⁰ Two more of these were found in the House with the Press and the North House. From the area south of the house come fragments of several crucibles containing slag and copper prills, lost-wax moulds, including one for a double axe, and clay material which was apparently stored in a vessel, possibly for making moulds and crucibles.

It is difficult to say whether the three LM IIIB deposits are related to one another. The material from the Northeast Room may be only household metal items and sharpening tools, though some possible slag from there indicates otherwise. Most of the hearths in the area seem to be closely connected to food preparation, though Blitzer proposes that the hearths in the house and an area with a burnt floor with clay-covered pits to the east of the house may remain from metal working, and that the inhabitants here moved from space to space to carry out metalworking during the LM IIIA2-B period.⁴⁷¹ At the very least, bronze double axes were produced here. The anvil/mould and hammering stones could have been used to forge the axes after casting, and the whetstones and emery cobble may have been used to sharpen them. The bronze rods may also have been forged into items. The anvil/mould could have been used with the stone hammers for sinking, though there is nothing to indicate what may have been produced here in this manner.

possible activities: lost-wax casting of bronze double axes, forging, finishing, ?sinking

§5.4.4. House with the Press: MM-LM and LM IIIA-B⁴⁷²

equipment: crucibles containing slag and bronze prills, lost-wax mould for a double axe, pumice tools, stone anvil/mould

waste: slag, prills, bronze fragments

⁴⁷⁰ Blitzer, "Minoan Implements and Industries," 486, no. GS 701, pl. 8.59C; McEnroe, "The Late Minoan Period," 230.

⁴⁷¹ Blitzer, "Minoan Implements and Industries," 530.

⁴⁷² Ibid; M. C. Shaw, "The House with the Press," in *Kommos I: Part 2*, ed. Joseph W. Shaw and Maria C. Shaw (Princeton: Princeton University Press, 1996).

The metallurgical material here dates to various parts of LM IIIA-B. One piece of slag is dated MM to LM. The crucibles and mould indicate that double axes were cast here. The anvil/mould and pumice tools could have been used to forge and sharpen the axes. Sinking may also have been carried out in the anvil/mould. Shaw proposes that Space 2 of the house may have been a depot where people obtained metal scrap and says that metalworking could not have taken place because there was no hearth here,⁴⁷³ but it is rare for any Minoan metallurgical material to be definitively linked with a hearth anyway.

possible activities: lost-wax casting of bronze double axes, finishing, forging, ?sinking

§5.4.5. North House⁴⁷⁴

LM IIIA1-2

equipment: lost-wax mould, probably for a double axe; crucibles; possible hearth indicated by burning over the floor

waste: slag

possible activities: casting of double axes by lost-wax casting

LM IIIB

equipment: pot bellows, crucible containing slag and prills, three lost-wax moulds for double axes, pumice, stone hammers, stone ?anvil/mould

waste: slag, prills, pieces of bronze

All of the evidence suggests that double axes were cast, forged and finished or sharpened here during this period. Sinking may also have been carried out with the anvil/mould, which is the same type as those found in the House with the Snake Tube and the House with the Press. It is possible that the evidence for metal working here in LM IIIA1-2 and in LM IIIB represent continued activity rather than two separate installations.

possible activities: lost-wax casting of double axes, finishing/sharpening, forging, ?sinking

⁴⁷³ Shaw, "The House with the Press," 127.

⁴⁷⁴ Blitzer, "Minoan Implements and Industries."; Shaw, "The North House and Peripheral Areas."

The five metallurgical installations in the Kommos houses indicate that several groups in the town were undertaking small-scale metalworking here during this period. This contrasts with the earlier MM III-LM I evidence from the southern harbour complex which appears to represent larger-scale, concentrated production.⁴⁷⁵ The change to smaller crucibles in the houses reflects the small-scale household industries which LM III Kommos metallurgy apparently comprised. Most of the installations here were involved in casting double axes. According to Blitzer, the inhabitants were using stone axes, indicating that bronze axes were produced here for an external market.⁴⁷⁶

§5.5. Malia – North-West Quarter of the Palace: MM III⁴⁷⁷

Malia, a palatial centre on the north-central coast to the east of Knossos, provides metallurgical materials from Protopalatial MM II (§5.6 below) and early Neopalatial MM III. The MM III material, found in the vicinity of the palace at Malia, appears to have been connected to the palace during this period. The material is not known to be connected to any particular structure.

equipment: possible hearth indicated by the presence of a burnt spot;
open stone moulds for rectangular and circular billets, bars, kite-shaped
billets; several two-piece stone moulds for double axes; bronze chisels,
and a ?pick

waste: ?slag

The slags and the burnt soil in which the material was found could be indicative of the remains of a hearth, but it is uncertain whether or not these are connected with the moulds. Pelon proposes that the slags and ‘furnace’ remains might be indicative of the smelting of rich copper ores in crucibles.⁴⁷⁸ However, the occurrence of smelting here is unlikely (see §4.1 on the absence of smelting in Crete after the Prepalatial period).

Whether or not the moulds are related to the slags and the burnt spot, they do represent an important casting installation, apparently producing utilitarian items. The

⁴⁷⁵ Blitzer, “Minoan Implements and Industries,” 528.

⁴⁷⁶ L. V. Watrous, “Late Bronze Age Kommos: Imported Pottery as Evidence for Foreign Contact,” *Scripta Mediterranea* 6 (1985): Harriet Blitzer in subsequent discussion, 17; Blitzer, “Minoan Implements and Industries,” 531.

⁴⁷⁷ Chapouthier and Demargne, *Palais III*, 24, 56-66; Pelon, “New Data from Malia.”; Evelyn, *Minoan Crafts* 2, 38, 356, 358.

⁴⁷⁸ Pelon, “New Data from Malia,” 271 and addendum.

material's proximity to the MM III palace may indicate that these are the remains of a palatial workshop. The billets which were cast in the stone moulds were probably forged into items, though apparently none of the forging equipment survives. The circular billets which were cast from the extant moulds may have been hammered into vessels, though mirrors may also have been made from them. The chisels and ?pick may have been products of the installation rather than equipment, though the chisels could have been used for breaking up metal to be melted down.

possible activities: open-mould casting of billets and bars, bivalve-mould casting of double axes, ?forging, ?breaking up, ?vessel production

§5.6. Malia – Quartier Mu: MM II (Figure 168)

Quartier Mu, a set of buildings adjacent to the palace at Malia, contained the workshops of several crafts, but also seems to have served an administrative function by MM II. Evidence for metalworking is scattered throughout Quartier Mu. The area which shows the strongest evidence for concentrated metalworking is the Founder's Workshop, which was contained within a two-storey building in which the artisans lived and worked and which lay adjacent to workshops for seal-makers and potters. The South Workshop, at the southern edge of the Quartier Mu complex, also contains a fair amount of evidence for metalworking. Further evidence occurs in Building B, in the vicinity of Building C, and in the North Area.

§5.6.1. Founder's Workshop⁴⁷⁹

equipment: stone pestle, cobble and pebble hammers; several schist moulds, some burned, including an open schist mould for 3 chisels and a ?pick, a mould for a double axe and a possible mould cover

waste: slag

finished objects: nail, needle, bronze drill

The workshop here was clearly producing bronze tools including double axes and chisels by casting in open and/or bivalve stone moulds. These may afterwards have

⁴⁷⁹ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 45-57, 115-118; J.-C. Poursat and C. Oberweiler, "Metalworking at Malia Quartier Mu: High or Low Technology?" in *Metallurgy: Understanding How, Learning Why: Studies in Honor of James D. Muhly*, ed. Philip P. Betancourt and Susan C. Ferrence (Philadelphia: INSTAP Academic Press, 2011).

been forged with the stone hammers. The smaller items found in the workshop, the drill, nail/rivet and needle, could have been made here by smaller-scale casting and forging.

possible activities: casting of bronze tools in open and bivalve moulds, forging

§5.6.2. South Workshop⁴⁸⁰

raw materials: lump of copper

equipment: stone ?pestle and cobblestone hammers, grinding tools, chisel, drill/nail

waste: slag

finished objects: saws, razor, ?pick, spear tip, needles, hook, fragment of a tripod foot, ?vessel rim, rivets, copper strip, small piece of gold

The evidence suggests that hammering and finishing took place here. The chisel may have been equipment or a product. Breaking up, forging and finishing are all that would have been required to make some of the simpler items found here such as razors, needles, hooks and rivets. The other items would have required casting facilities, which the slag indicates may have existed here. The possibility that vessel-making took place here is indicated by the fragment of the tripod foot and the possible vessel rim, though these might also be scrap to be melted down. Gold work may also have been carried out here, possibly for jewellery-making. Poursat and Oberweiler suggest that the workshop here was not specialised, producing stone vases and perhaps bone objects in addition to bronze items.

possible activities: forging, finishing/sharpening, breaking up, drilling, casting, ?vessel-making, jewellery making

§5.6.3. Building B⁴⁸¹

raw materials: copper strip

equipment: crucible

⁴⁸⁰ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 59-68, 115-118; Poursat and Oberweiler, "Metalworking at Malia Quartier Mu."

⁴⁸¹ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 71, 115-118; Poursat and Oberweiler, "Metalworking at Malia Quartier Mu."

Products: saw, double axe, adze, tweezers, awl

The crucible is the only evidence of any metalworking here. Some of the tools here come from a deposit which is considered by Poursat to be that of a carpenter. Some small-scale casting may have occurred here, but since the crucible is quite small, there is insufficient evidence to point to the production of the large tools found here.

possible activities: casting

§5.6.4. Building C and Vicinity⁴⁸²

equipment: blackened ?bivalve schist mould for a double-axe, three tuyères

finished objects: saw fragments

The evidence indicates that double axes were produced here. The saw fragments may just as well be scrap for melting down as products of the installation.

possible activities: casting of double axes in two-piece stone moulds

§5.6.5. North Area and Vicinity⁴⁸³

equipment: tuyère, ?bivalve schist mould for a double axe

As for Building C and its vicinity, it appears that double axes were produced here.

possible activities: casting of double axes in ?bivalve schist moulds

§5.7. Mochlos Settlement: Pre-LM IA to LM III (Figure 169)⁴⁸⁴

Neopalatial and Postpalatial remains of the settlement at Mochlos, located east of the Bay of Mirabello on the north-east coast, contained metallurgical materials spread through several houses. The excavations have not yet been published in full, so the information presented here may not be complete. Information about any stone tools would assist in determining whether the following material represents actual metal-

⁴⁸² Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 69, 115-118; Poursat and Oberweiler, "Metalworking at Malia Quartier Mu."

⁴⁸³ Poursat, *Artisans minoens: les maisons-ateliers du quartier Mu*, 115-118; Poursat and Oberweiler, "Metalworking at Malia Quartier Mu."

⁴⁸⁴ Brogan, "Metalworking at Mochlos."; Soles, "Metal Hoards."

working activities. Some of the larger crucibles show signs of burning on the inside, which may indicate that they were used as crucible hearths.

§5.7.1. House C2: LM IA

raw materials: bronze discs 150 mm in diameter

equipment: crucibles, one 120 mm high, some burned on the inside

The discs may have been blanks for vessel manufacture, or for scale pans or mirrors. The crucible with burning on the inside may have been used as a crucible hearth for producing small items.

possible activities: casting, production of small items, ?vessel-making

§5.7.2. House C7: LM IA

raw materials: oxhide ingot fragments, damaged bronze tools and vessels, bronze scraps

equipment: pot bellows, crucibles, the largest 200 x 250 mm in diameter

waste: scrap

The evidence here indicates casting of some kind, though it is not clear what was being cast. It appears that recycling was taking place. The large size of the crucible suggests that large objects were being cast. In the same house, the presence of slag in MM levels indicates that casting was also taking place here earlier.

possible activities: casting of large items, recycling

§5.7.3. House C3: Pre-LM IA Early LM IB, Later LM IB

raw materials: bronze hoards (see below)

equipment: bellows' nozzle, pumice

The early LM IB material from House C3 includes a pot bellows' nozzle and from later LM IB deposits come two bronze hoards. One of these includes ingot fragments, tongs, balance pans and many damaged items such as tools, vessels and weapons, but according to Soles it is likely to be a hoard of a household treasury rather than a

workshop scrap supply.⁴⁸⁵ Another hoard, containing exactly half an oxhide ingot, a sistrum and many intact items such as tools, weapons and vessels was probably a trader's hoard.⁴⁸⁶ A pre-LM IA hoard containing a shovel and two double axes was probably a foundation hoard deposited for a deity's blessings.⁴⁸⁷

The bellows' nozzle and a large deposit of pumice just outside the house may therefore be the only evidence of metal-working here. These indicate casting and possibly finishing.

possible activities: casting, ?finishing

§5.7.4. House Alpha: LM III or Neopalatial

equipment: pot bellows' nozzle

waste: slag

Slag and a pot bellows' nozzle dating to LM III are the only metallurgical evidence from House Alpha. According to Brogan, this may be Neopalatial material.⁴⁸⁸

possible activities: casting

§5.7.5. House Mu: LM III or Neopalatial

equipment: clay mould (unspecified type, probably lost-wax), possibly for a double axe

waste: slag

This material, indicative of casting, is dated LM III, though as for the House Alpha material, this may be Neopalatial material.⁴⁸⁹

possible activities: ?lost-wax casting

Because the material has not been fully published at the time of writing, it is difficult to draw many conclusions about metal-working activities taking place in the houses. The

⁴⁸⁵ Soles, "Metal Hoards," 147, Hoard 2.

⁴⁸⁶ Ibid., 148-152, Hoard 4.

⁴⁸⁷ Ibid., 151-152, Hoard 6.

⁴⁸⁸ Brogan, "Metalworking at Mochlos," 165-166.

⁴⁸⁹ Ibid., 165-166.

presence of slag deposits must surely be evidence of metallurgical activity, and it seems unlikely that crucibles, moulds and pot bellows would be kept in houses where no activity was taking place. It appears that some metal-working was carried out in House C2 during LM IA, perhaps casting, though the crucibles may have been crucible hearths, and the bronze discs may indicate that vessel manufacture was carried out there. Casting probably took place in House C7 some time during MM, and almost certainly did during LM IB. The large crucibles may be indicative of some large-scale casting taking place here. Although the various hoards from House C3 contain some excellent examples of metal-working tools and products, the evidence for actual metal-working is minimal. Casting was probably carried out in Houses Alpha and Mu during either the Neopalatial period or LM III.

It is not exactly clear what was being produced here. However, if we take it that the many hoards found at Mochlos are in fact the products of these workshops or installations, then these were clearly skilled and versatile smiths, producing the whole corpus of Minoan bronze items both utilitarian and luxury. It is also possible, however, that most of these items were the products of the better-equipped Artisans' Quarter discussed below.

§5.8. Mochlos Artisans' Quarter: Final LM IB (Figure 170)⁴⁹⁰

The Artisans' Quarter at Mochlos appears to have contained the residences of independent artisan families who lived and worked within the buildings.⁴⁹¹ Evidence for metalworking was spread throughout Buildings A and B, though Building A contained more material than B. It is difficult to say whether the two buildings contained independent workshops or whether they were one combined workshop, but each building appears to contain a range of equipment which would have enabled them to be independent of one another. Building A also contained a workshop for stone vase manufacture, and Building B for pottery and textiles.

⁴⁹⁰ J. S. Soles, "Conclusions on the Artisans' Quarter," in *Mochlos IA*, ed. Jeffrey S. Soles and Costis Davaras (Philadelphia: INSTAP Academic Press, 2003); Soles, "The Metal Finds."; Soles, Nicgorski, and Soles, "Ceramic Objects."; Carter, "The Stone Implements."; Brogan, "Metalworking at Mochlos."

⁴⁹¹ Brogan, "Metalworking at Mochlos," 161.

§5.8.1. Building A

raw materials: copper ingot fragments, metal scrap including a lekane, hinges, bowls, tweezers and lekane handle

equipment: ?limestone anvils, stone hammers, polishers and whetstones; pumice tools, open clay mould for a billet, bivalve stone mould for a ?rivet, lost-wax moulds for vessel handles, and an axe or chisel, a lead weight, copper strip possibly used for binding mould halves

waste: copper and bronze casting spill

products: hook, knives, fish hook, earrings, pin

The evidence here indicates extensive production of small and large bronze items. The lead weight may have been of use in the production of alloys. Billets and smaller items were cast in open and bivalve moulds, and tools by lost-wax casting. The tools could then be forged with the anvils and hammers, and sharpened with the various whetstones and finishing tools. The workshop was also well equipped for making smaller bronze items such as the hook, knives, earring and pin found here, by casting, forging and finishing.

The moulds for the vessel handles suggest that vessel manufacture was also carried out here, as do the vessel scraps. The stone hammers and various finishing tools could also have been used for vessel production.

possible activities: alloying and production of bronze tools, vessels, domestic items and jewellery by hammering, casting with open and bivalve moulds and by lost-wax casting, and finishing

§5.8.2. Building B

raw materials: copper ingot fragments, scrap

equipment: ?lost-wax mould for a small billet, whetstones, hammer stones, abrading/finishing stones, polishing stones, ?balance weights, copper strip possibly used for binding mould halves

waste: copper and bronze casting spill

products: chisel, needle, earrings, spatula/scrapper

The evidence here suggests the production of small utilitarian items and jewellery in bronze by casting, forging and finishing. Some alloying may also have taken place

possible activities: ?alloying, lost-wax casting, forging and finishing of small items

Building A seems to have been better-equipped than B, at least at the time that the site was abandoned, and was producing many bronze items of the Minoan corpus. The metalsmiths in Building B were perhaps producing smaller items. The distribution in the settlement of the types of items produced by the artisans not only in metal but also clay and stone suggests that the occupants of the Artisans' Quarter were producing utilitarian objects for the surrounding community as well as for wider communities.⁴⁹²

§5.9. Palaikastro: LM IIIA2 or LM IIIB⁴⁹³

The metallurgical evidence from Palaikastro, a settlement on the east coast, consists of a deposit of metallurgical debris mixed with pottery sherds and stones. Since the deposit consists only of the waste of metallurgical processes, some metallurgical evidence is lacking. If this was indeed a deposit of rubbish, as it appears to be, it is unlikely that reusable equipment such as hammers, for example, would be found here. It was not possible to pinpoint the location of the activities.

The deposit was located against a terrace wall amongst buildings which were occupied until LM IIIB. The deposit is dated by Hemingway to LM IIIB according to pottery sherds in the deposit. Catling argues, however, that an LM IIIA2 date is more appropriate. Catling also argues against Hemingway's identification of several mould fragments, particularly those which Hemingway identifies as being from the production of Late-Cypriot-type tripod stands.

equipment: tuyères (at least eight), large crucibles, lost-wax moulds for the following items: doubles axes, axes, ?sickles, billets, a ring-type vessel handle, parts of a tripod stand including rods, double and triple rods, volutes and decorative elements

waste: slag, bronze prills

⁴⁹² Ibid., 161; Soles, "Conclusions on the Artisans' Quarter," 91-100.

⁴⁹³ Hemingway, "Minoan Metalworking in the Postpalatial Period.," H. W. Catling, "Minoan Metalworking at Palaikastro: Some Questions," *BSA* 92 (1997).

The presence of the tuyères and the large crucibles alone indicates that casting of large-scale items in bronze occurred here. These objects included tools and some more decorative items. Whether or not tripod stands were being cast, the moulds do show at least that decorative items were being made. The presence of the ring-type handle moulds indicates that cauldrons were produced here. Hemingway provides a reconstruction of a cauldron mounted on a tripod stand which incorporates the type of handle which the mould might produce. This type of handle is also found on some of the LM IIIA type 7A tripod cauldrons (see figure 7). No extant cauldrons of this type have a diameter as large as the 700 mm cauldron which Hemingway proposes that these handles were made for.

possible activities: casting of small and large items by lost-wax casting including tools and decorative items; vessel construction

§5.10. Poros-Katsambas⁴⁹⁴

Poros-Katsambas, located on the central north-coast, was the harbour town of Knossos.

As of writing, the metallurgical material from this site has not yet been published in full, and it is currently possible to determine only in broad terms what metallurgical activities were carried out in the town. It is not yet easy to distinguish any one installation or workshop. The town appears to have been a manufacturing centre employed in several crafts. Some important pieces of equipment are as yet unconnected to any structure or period, including pot-bellows and bivalve clay moulds for axes and daggers.

§5.10.1. MM IIB

Skatzourakis' Plot

equipment: large crucible

waste: "by-products of copper melting"

possible activities: casting of large items

⁴⁹⁴ Dimopoulou, "Workshops and Craftsmen in the Harbour-Town of Knossos at Poros-Katsambas."

§5.10.2. MM III – LM I

Charonitakis' plot

equipment: crucibles, tuyères, stone bivalve mould for beads

waste: slags, droplets

The presence of the tuyères indicates that casting of large items occurred here alongside bead-casting, which would have required the use of only a small draught source.

possible activities: casting of small items (?jewellery) and large items

Psychogioudakis' plot

raw materials: “raw material”, lead ingot

equipment: crucibles, clay-lined hearth, stone tools, clay mould for female-figure-shaped pendant, pumice tools

waste: slags, scraps, “waste”

finished objects: lead vessel

possible activities: lead work, casting of small jewellery items, finishing

Sanoudakis' plot

raw materials: copper ingots, copper/bronze rods, strips, pellets and wire

equipment: crucibles, tuyères, clay moulds for beads and ornaments, drills, blades, chisel, sharpening stone tools, lead weights, stone anvil, pumice tools

waste: droplets, slags

The evidence here indicates a casting installation. The moulds suggest that small jewellery items were cast, but the presence of tuyères suggests that casting of large items was also carried out. Some hammer-work may also have been performed. Apparently the artisans here undertook a variety of crafts, since there is also evidence of seal-stone and bead production in semi-precious stones, and of ivory- and paste-working. Some of the equipment listed above is applicable to these crafts also. The working area is two rooms in a large, well-appointed building. Dimopoulou suggests that the house was occupied by the artisan(s).

possible activities: casting of small and large items, hammering,
finishing, breaking up, jewellery production

§5.10.3. LM IIIA2-B

Sanoudakis' Plot

equipment: hearth/furnace

waste: "by-products of metal-melting"

possible activities: casting

§5.10.4. Mixed LM I to LM III context

Trypeti Hill

raw materials: oxhide ingot

equipment: crucibles, including one very large (250 mm diam.)

possible activities: casting of large items

§5.11. Zakros: LM IB (Figure 171)

Two locations at Zakros, a palatial centre on the east coast, provide small amounts of evidence for metalworking: in the south wing of the palace and in the House of Niches. Ingot remains in the west wing are probably the remains of a store rather than of a metalworking facility, since other precious materials were also found nearby, and there is no other metallurgical evidence in the vicinity other than a possible anvil/stake (see §4.4.2). The 'fingered' kiln at the northeast of the palace is probably a pottery kiln, rather than a metalworking kiln as Platon identifies it (see §4.2.2).

§5.11.1. Palace South Wing⁴⁹⁵

raw materials: bronze sheet

Platon identifies a room above rooms XLIII, XLV and XLVa as a metal workshop owing to the presence of sheet metal in the fall from the upper storey in these rooms. This is very slight evidence, but the added presence of the remains from other crafts in

⁴⁹⁵ Platon, *Zakros*, 211.

the building means that metalworking may have been carried out somewhere in the building.

possible activities: ?sheet-working

§5.11.2. House of Niches⁴⁹⁶

equipment: grinding stones, ?charcoal, crucibles

Evely says that the metallurgical material may have been earlier material moved to the site during building. The evidence suggests casting and finishing (**figure 171**).

possible activities: casting, finishing

§5.12. Vessel Production at the Sites

Almost all of the metallurgical sites discussed here show evidence for casting. Generally, the evidence indicates casting of bronze tools in open, bivalve and lost-wax moulds. Tools for finishing are also quite common. Since casting remains are often the only means for identifying a metalworking site, our understanding of the distribution of metalworking is skewed.

Often the presence of the evidence from some processes indicates that other processes must also have taken place there. For example, since many cast tools required alloying, annealing, forging and finishing, it is likely that these processes also occurred at the sites where tool-casting took place, though the evidence may be lacking.

The evidence for vessel production at any of the sites is disappointing. Only five of the sites show any evidence, and it is minimal. The remains of lost-wax moulds for vessel handles in Building A at the Mochlos Artisans' Quarter during LM IB and at Palaikastro during LM IIIA2 or B provide indirect evidence of vessel production, if one assumes that vessel attachments were produced in the same workshop or installation as the vessels themselves. Likewise, the parts of vessel attachments in the South Workshop at Quartier Mu may indicate vessel production, though these may be scrap collected from elsewhere. The bronze discs in House C2 at Mochlos during LM IA may have been intended for vessel production, but may also have been made into mirrors. Likewise, the MM III disc-moulds in the north-west quarter of the palace at Malia may have been for vessel-production.

⁴⁹⁶ Evely, *Minoan Crafts* 2, 341.

§5.13. The Social Positions and Social Structures of Metalworkers

A number of models for the social position and structures of craft workshops in prehistory have been proposed to suit different political and economic systems. Costin proposes eight models for workshop structure ranging between the extremes of the independent specialist to a retainer workshop.⁴⁹⁷ A retainer workshop is administered by an elite authority which controls the workshop output to maintain authority. The goods produced are luxury or wealth-generating items and weapons and have political and social significance which allows the elite patrons “to finance their activities, and to control the ideology and technology of power”.⁴⁹⁸ The retainer workshop craft specialist is highly skilled, probably works at the craft full time, his subsistence attended to by the patron, and manufactures on demand. The workshop itself is located close to the patron. At the other end of the scale is the independent specialist. This individual is autonomous, producing utilitarian items for an unrestricted market. He works at the craft part time from home as a means of augmenting his more usual means of subsistence, agriculture, for example. The labour force within this workshop is more likely to be kin than in a retainer workshop, although others may be brought in if the production unit grows.

Costin describes other models which vary between these two extremes according to varying social contexts, concentration and scale of the workshops, and schedule intensity. An independent specialist workshop might run full time if the products are in such high demand that the worker or workers do not have to work for subsistence. Alternatively, a workshop might be independent, producing utilitarian items for a community, but also employed part time to produce elite items.

The extremes of retainer workshop versus part-time, independent specialist have been criticised as being too simplistic.⁴⁹⁹ Based on interpretation of Linear B tablets from Pylos, Gillis proposes a model wherein a smith works part-time and pays taxes to the palatial administration in the form of produced goods.⁵⁰⁰ Another possible system is exemplified by an ethnographic example from Myanmar. Smiths in Northern Chin

⁴⁹⁷ Costin, “Craft Specialisation: Issues in Defining, Documenting and Explaining the Organization of Production.”

⁴⁹⁸ *Ibid.*, 13.

⁴⁹⁹ Brysbaert, *The Power of Technology*, 30-32; C. Gillis, “The Smith in the Late Bronze Age - State Employees, Independent Artisan, or Both?,” in *TEXNH*, ed. Robert Laffineur and Philip P. Betancourt, Aegaeum 16 (Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique, 1997), 513.

⁵⁰⁰ Gillis, “The Smith in the Late Bronze Age - State Employees, Independent Artisan, or Both?”

tribes here, who are local officials, are paid taxes in return for working exclusively for their communities.⁵⁰¹

I will not venture to draw conclusions as to the type of roles metalsmithing workshops played in Minoan socioeconomic systems, because there is too little evidence to reach any satisfactory conclusions. Evelyn has suggested that, at least during the palatial periods, craft work-forces were semi-free to some extent, although slave labour was also used and controlled by a fairly complex bureaucracy. He acknowledges too that private enterprise was probably also present.⁵⁰²

As was discussed in §1.3, it is almost certain that metal vessels were produced for elite consumption. The amount of labour and materials required to make many of them would have made them very valuable. Furthermore, the hierarchy of vessels used for feasting indicates that most metal vessels were probably restricted in their circulation in order to maintain social stratification. Within Costin's system, smiths producing such items would work in retainer workshops, which would allow palatial administrations to limit vessel production. It is also possible, however, that they were produced in workshops which operated part-time to produce such items, in independent workshops where vessels were paid as tributes or taxes, or by smiths who were valued for their skills to the extent that they were paid to remain loyal to patrons, thus reducing the circulation of vessels. However, since we have discovered in this study that the equipment required for making vessels was not especially difficult to come by, it is also entirely possible that an independent smith who usually produced utilitarian items for a community may have made some of the less labour-intensive and material-rich vessels such as bowls and smaller basins.

⁵⁰¹ M. Rowlands, "The Archaeological Interpretation of Prehistoric Metalworking," *World Archaeology* 3, no. 2, Archaeology and Ethnography (1971): 214.

⁵⁰² Evelyn, *Minoan Crafts* 2, 565.

The Examination of Individual Minoan Vessels

For this study, I made a close inspection of seventeen Minoan vessels in Crete and Britain. In October 2009 I examined six vessels in the Chania Archaeological Museum. During May and June 2010, I examined five vessels in the Ashmolean Museum and one vessel in the Ayios Nikolaos Archaeological Museum. I also returned to the Chania Archaeological Museum to examine four Minoan vessels in the Mitsotakis Collection and I was permitted to examine one vessel held by the British School at Athens in Palaikastro. Unfortunately, I was not able to access any material in the Heraklion Archaeological Museum where the bulk of Minoan vessels are held. I believe that, overall, the vessels I have examined provided an adequate sample and that the study was not overly affected by this unfortunate situation.

Most of the vessels examined have previously been catalogued by Matthäus.⁵⁰³ Those which have not include a one-handled basin from Palaikastro which, to my knowledge, has not been published, and the vessels from the Mitsotakis Collection. This collection was not published until 1992, 12 years after *BKMK*.⁵⁰⁴ However, perhaps for some specific reason, these vessels do not seem to be cited in later publications, including Hakulin's 2004 catalogue of LM bronze material.⁵⁰⁵

§6.1. The Vessels Examined

The vessels are arranged here according to Matthäus's typology.⁵⁰⁶ I have attempted to classify those not in Matthäus's catalogue. These are marked with an asterisk next to the type number. Periods given are from *BLMC* unless otherwise indicated.⁵⁰⁷

Following the description of each vessel, the process used to make it is described. I determined these processes based on observation and my own experience and knowledge of vessel manufacture.

⁵⁰³ Matthäus, *BKMK*.

⁵⁰⁴ M. Tsipopoulou, "Minoan Metal Vases and Vessels," in *Minoan and Greek Civilization from the Mitsotakis Collection*, ed. Lila Marangou (Athens: N. P. Goulandris Foundation - Museum of Cycladic Art, 1992).

⁵⁰⁵ Hakulin, *BLMC*.

⁵⁰⁶ Matthäus, *BKMK*.

⁵⁰⁷ Hakulin, *BLMC*.

§6.1.1. Two-Handled Pan (Figures 172, 173 and 174)⁵⁰⁸

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M119
BKMK Type	4A
BKMK no.	30
Dimensions	h. 95-100, rim diam. 314, base diam. 282 ⁵⁰⁹
Appendix 1 no.	144

Description

A broad, shallow pan with a slightly convex base, straight, slightly everted walls and a folded-out rim. Two loop-handles sit halfway down the wall on opposite sides. Part of the wall is missing; there is a small hole in the base caused by corrosion and a small tear in the rim. The surface is moderately corroded and is scratched, probably from modern corrosion removal.

The rim is 9-10 mm wide, 1.6 thick at the edge, 1.2 in the centre and 1 mm at the fold. The wall thins to 0.6 mm at 5 mm down from the rim, to 0.5 mm in the middle and thickens to 0.9 mm at 15 mm above the base. The hole in the base, close to the junction with the wall, reveals the base to be 1 mm thick here.

The handle-loop is rectangular in section and has rectangular, vertical attachment-plates which are splayed at each end (**figure 175**). Each plate is fixed to the wall with two flush rivets, the inside head diameters being 12 mm and the outside 5 mm (**figure 176**). These handles are almost identical to those of the tripod pan also from Chania (see §6.1.2 below). The two probably came from the same workshop.

Method of Construction

The billet was hammered thin and concave,⁵¹⁰ the walls raised and the base flattened. The rim was probably partially caulked during the shaping rounds and folded over afterwards. The handles were made by lost-wax casting and may have been forged slightly.

⁵⁰⁸ F. Matz, *Forschungen auf Kreta* (Berlin: Verlag Von Walter De Gruyter & Co, 1951), 74, no. M 119; Popham, Catling, and Catling, "Sellopoulo," 249, no. 5a.1; Matthäus, *BKMK*, 96, no. 30, pl. 5.30; Hakulin, *BLMC*, Appendix V.2/27, no. 860.

⁵⁰⁹ Matthäus, *BKMK*, 96.

⁵¹⁰ Wherever this method is mentioned, the techniques which would have been used are sinking, spiral-forging or a combination of the two, since these are the only techniques which can be used to do this. These are described in §2.1.4.

§6.1.2. Tripod Pan (Figures 177 and 178)⁵¹¹

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M118
BKMK Type	4B
BKMK no.	36
Dimensions	total h. 140, h. body 110, rim diam. 354-358, base diam. 323 ⁵¹²
Appendix 1 no.	145

Description

A broad, shallow pan with a slightly convex base, straight, slightly everted walls and a folded-out rim. There are two loop-handles halfway down the wall on opposite sides of the pan and three short legs, one of which is missing, are attached at the junction of the wall and the base. A large section is missing from the wall and base of the pan and other smaller pieces from the wall and base. There is a moderate amount of surface corrosion and scratches, probably from modern corrosion removal.

The rim is 10 mm wide and the material 1.6 mm thick at the edge. The wall is 0.9 mm thick 30 mm down from the rim, and halfway down thins to 0.6 mm before thickening again at the junction of the base and the wall to 0.9 mm. The base is 0.6 mm thick at 10 mm in from the wall, thickens to 1 mm halfway between the wall and the centre, and 1.1 mm at the centre.

The handle-loops are square in section and terminate at each end with a rectangular, vertical attachment-plate (**figure 179**). Each plate is fixed to the wall with two flush rivets with inside-head diameters of 15 mm and outside of 7 mm. There are two small, opposing chevrons cut into the handle-loops. The handles are almost identical to those on the two-handled pan above (§6.1.1). The two probably came from the same workshop.

The legs are short, raising the base approximately 30 mm (**figure 180**). The leg extends up the wall, where it is attached by one flush rivet, and has a bracket reaching under the base attached by one flush rivet (**figure 181**). The rivet-head diameters are 7

⁵¹¹ Matz, *Forschungen auf Kreta*, 74, no. M 118; Popham, Catling, and Catling, "Sellopoulo," 249, no. 5b.3; Matthäus, *BKMK*, 96, no. 36, pl. 6.36; Hakulin, *BLMC*, Appendix V.2/27, no.861.

⁵¹² Matthäus, *BKMK*, 96-97.

mm on the outside and 15 mm on the inside. The front of each leg is decorated with a small, out-turned foot and two vertical grooves.

Method of Construction

The billet was hammered thin and concave, the walls raised and the base flattened. The rim was probably partially caulked during the shaping rounds and folded over afterwards. The handles and legs were made by lost-wax casting.

§6.1.3. Restored Two-Handled Pan (Figures 182 and 183)⁵¹³

Period	LM IIIA1 ⁵¹⁴ or LM IIIB ⁵¹⁵
Site	Knossos, Zapher Papoura Tomb 99
Collection	AshM AE494
BKMK Type	4 Varia
BKMK no.	38
Dimensions	h. 65-68, rim diam. 248, base diam. 217-219 ⁵¹⁶
Composition	Cu 88, Sn 9.1, Pb 1.1 ⁵¹⁷
Appendix 1 no.	180

Description

Heavily corroded and heavily restored two-handled basin with a broad, flat base, straight, vertical walls, and an out-turned rim. The handles are wishbone-type, each with two attachment-plates (**figure 184**), attached to the wall each with one flush rivet. Due to corrosion and subsequent restoration, the original height of the vessel is unknown. The restored height is consistent with similar vessels. The only observable thickness measurement is at the edge of the rim, which is 1.5 mm.

⁵¹³ A. J. Evans, *The Prehistoric Tombs of Knossos*, *Archaeologia* 59 (1906), 89, no. 99g, fig. 100g; O. Montelius, *La Grèce préclassique*, 2 vols., vol. 1 (Stockholm: Haeggströms, 1924), pl. 33:5; Catling, *CBMW*, 171, no. 5a.3; Matthäus, *BKMK*, 99, no. 38, pl. 6.38; Hakulin, *BLMC*, Appendix 5.1/6, no. 153, Appendix 5.2/27, no. 895.

⁵¹⁴ Hakulin, *BLMC*.

⁵¹⁵ Catling, *CBMW*.

⁵¹⁶ Matthäus, *BKMK*, 99.

⁵¹⁷ Hakulin, *BLMC*, Appendix V.1/6, no. 153.

Method of Construction

The billet was hammered thin and concave, the walls raised and the base flattened. The rim was folded over afterwards and the handles made by lost-wax casting.

§6.1.4. Tripod Cauldron (1) (Figures 185, 186 and 187)⁵¹⁸

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M116
BKMK Type	6
BKMK no.	44
Dimensions	h. 328, diam. 298 ⁵¹⁹
Appendix 1 no.	142

Description

The body has a rounded base, high, slightly everted walls and a folded-out rim. There were originally two horizontal loop-handles, one of which is missing, attached immediately under the rim on opposite sides of the vessel. Three legs are fitted at the junction of the wall and the base. A large section of the wall, where the second handle was, is missing and there are holes and cracks in the base and rim. There is a moderate amount of surface corrosion and the surface is scratched, probably from modern corrosion removal.

The rim is 11-12 mm wide and 1.2 mm thick at the edge. Due to the large section missing from the wall and the cracks in the base, the material thickness is observable along all of the profile except at the centre of the base. Where the rim folds out from the wall, the material is 1 mm thick. Halfway down the side of the wall it is 0.6 mm, and where the wall meets the base it is 1 mm. Near the wall, the base is 0.8 mm, and it thickens towards the centre, reaching 1 mm at 50 mm from the wall.

The loop-handles are ovoid in section and have horizontal attachment-plates fixed to the wall with one mushroom-head rivet per plate (**figure 188**). The bulbous rivet-heads are on the inside wall, with diameters of 11 mm, and the outer are 4-6 mm. The remaining handle has a central knob, or faux rivet, and opposing chevrons cut on either side of the knob.

⁵¹⁸ Matz, *Forschungen auf Kreta*, 73, no. M 116; Popham, Catling, and Catling, "Sellopoulo," 247, no. 4a.6; Matthäus, *BKMK*, 102, no. 44, pl. 7.44; Hakulin, *BLMC*, Appendix V.2/27, no. 862.

⁵¹⁹ Matthäus, *BKMK*, 102.

Each of the legs is trapezoidal in section, extends vertically into a decorative attachment-plate fixed to the wall with two mushroom-head rivets (**figure 189**) and has a bracket extending under the base attached with one mushroom-head rivet (**figure 190**). The bulbous heads, which are inside the vessel, are 12 mm in diameter, and the flush outer heads 5 mm.

Method of Construction

The billet was hammered thin and concave, the walls raised and the base left concave. The rim was probably partially caulked during the shaping rounds and folded over afterwards. The handles and legs were made by lost-wax casting.

§6.1.5. Tripod Cauldron (2) (Figures 191, 192 and 193)⁵²⁰

Period	Neopalatial
Site	Probably east Crete
Collection	AshM 1967.1213
BKMK Type	6
BKMK no.	69
Dimensions	h. 277, rim diam. 278-285 ⁵²¹
Appendix 1 no.	102

Description

The body has a rounded base, high, slightly everted walls and an everted rim. Two horizontal handles are attached immediately under the rim on opposite sides. A rim-loop is attached to the wall halfway between the two handles and overhangs the rim. The three legs are fitted at the junction of the wall and the base. The body had been broken into many pieces which are now reconstructed with filler and some unsealed cracks also remain. There is a moderate amount of corrosion over the surface and some parts, particularly the handles and legs, are badly corroded. One leg is broken off below the attachment-plate.

Unlike the tripod cauldron (1) described in §6.1.4, the rim is only curved out rather than folded out horizontally. The material thickness at the edge of the rim is 1.2 mm.

⁵²⁰ H. W. Catling, "Recent Acquisitions by the Ashmolean Museum, Oxford," *Archaeological Reports* 14 (1967-1968): 50; Popham, Catling, and Catling, "Sellopoulo," 247, no. 4a.8; Matthäus, *BKMK*, 104, no. 69, pl. 10.69; Hakulin, *BLMC*, Appendix V.2/27, no. 934.

⁵²¹ Matthäus, *BKMK*, 104.

Where the rim folds out from the wall, the material is 0.75 mm thick. The wall thins to 0.3 mm at 50 mm from the junction of the base. The rim-loop is attached to the wall with a single, flush-head rivet (**figure 194**).

The loop-handles are ovoid in section with horizontal attachment-plates fixed to the wall with one flush rivet per plate. The outer-head diameters are 8-10 mm and the inner 18-20 mm.

The legs are trapezoidal to ovoid in section and extend up to an attachment-plate fixed to the wall and a bracket under the base. The upper attachment-plate is attached with three flush rivets and the bracket with one. The outer rivet-head diameters are 8-10 mm and the inner 18-20 mm. On the broken leg, bubbles can be seen in the material where it has broken, indicating that it was cast (**figure 195**).

Method of Construction

The billet was hammered thin and concave and the walls raised. The base was left concave. The rim was probably partially caulked during the shaping rounds and folded over afterwards. The legs and handles were made by lost-wax casting and the rim-loop was forged from a small billet.

§6.1.6. Two-Handled Basin (Figures 196 and 197)⁵²²

Period	Neopalatial
Site	probably east Crete
Collection	AshM 1967.1216
<i>BKMK</i> Type	10C
<i>BKMK</i> no.	124
Dimensions	total h. 104, body h. 75, rim diam. 298-315 ⁵²³
Appendix 1 no.	103

Description

Basin with a broad, flat base curving up to straight, vertical walls. The rim is folded out and in and there were two vertical loop-handles. One is now missing. Most of the rim is missing, and the basin had cracked and corroded away in several places around the wall and base, but has been reconstructed. The remaining corrosion is moderate.

⁵²² Catling, "Recent Acquisitions," 50; Popham, Catling, and Catling, "Sellopoulo," 248, no. 7a.4; Matthäus, *BKMK*, 124, no. 124, pl. 15.124; Hakulin, *BLMC*, Appendix V.2/27, no. 935.

⁵²³ Matthäus, *BKMK*.

The rim-width is 10 mm and overhangs the inside by 3.5 mm (figure 198). The handle is a rounded square in section, and each end is slightly flat where it is fixed to the wall (figure 199). Each end was fixed with one mushroom-head rivet, the bulbous end on the inside, but only one rivet remains. The hole from the missing rivet is flared (figure 199), suggesting that it may have been made with a punch. The rim has hemispherical recesses cut into it so that the handles may rise through it. Halfway between the handles, a hole has been made through the wall, and there appear to have been two recesses in the rim on either side of this hole. It is unclear what these were for, but some equivalent to the rim-loop on the Ashmolean tripod cauldron (§6.1.5) is a possibility.

The material thickness of the rim varies between 0.75 and 0.9 mm. Where the holes have been made for the handle rivets, 15 mm below the rim, the material is 0.7 mm and the wall thins to 0.3 mm at the curve to the base.

Method of Construction

The billet was hammered thin and concave. The simplicity of its concave shape, with no ridge defining the base from the wall, indicates that it may have been formed without raising. The rim was probably caulked as for other folded rims, but this could not be confirmed. The rim was subsequently folded out and in, and the recesses cut for the handles. The handles were forged from bar.

§6.1.7. Pan with Hollow, Vertical Handle (1) (Figures 200 and 201)⁵²⁴

Period	Neopalatial ⁵²⁵
Site	probably east Crete
Collection	AshM 1967.1214
BKMK Type	13A
BKMK no.	166
Dimensions	total h. 135, body h. 57-63, rim diam. 258-262 ⁵²⁶
Appendix 1 no.	105

⁵²⁴ Catling, "Recent Acquisitions," 50; Matthäus, *BKMK*, 142, no. 166, pl. 19.166; Hakulin, *BLMC*, Appendix V.2/27, no. 936.

⁵²⁵ Hakulin, *BLMC*.

⁵²⁶ Matthäus, *BKMK*, 142.

Description

The pan has a flat base, low walls and a heavily-thickened rim. A tall, hollow handle from the same material rises vertically from the rim, tapering from top to bottom. The base, which had corroded away in parts, has been reconstructed with filler. There is light corrosion over the entire surface.

The rim has been caulked to 5-6 mm wide, overhanging the wall on both sides but more so to the outside, and is slightly curved on the upper edge. The hollow handle is formed from a wedge-shaped piece of sheet rolled into a tapered tube, the edges meeting behind (**figure 202**). The top edge of the handle material is 1 mm thick and splayed outwards. Lower down, the sheet thins to 0.4 mm thick. Where the handle rises from the rim, the rim is carefully shaped at the back so that the thick rim transitions into the sheet from which the handle is made.

Method of Construction

The billet had a bar extending from its edge as a provision for the handle to be hammered from. The disc of the billet was hammered thin and concave, the wall raised, and the base hammered flat. The rim was caulked between rounds. The handle provision was subsequently forged into sheet and rolled around a mandrel. Particular attention was paid to hammering the shoulders on either side of the handle to a smooth transition.

§6.1.8. Pan with Hollow, Vertical Handle (2) (Figures 203 and 204)⁵²⁷

Period	Neopalatial ⁵²⁸
Site	probably east Crete
Collection	AM no. 1967.1215
BKMK Type	13A
BKMK no.	167
Dimensions	total h. 150, body h. 57-65, rim diam. 271 ⁵²⁹
Appendix 1 no.	106

⁵²⁷ Catling, "Recent Acquisitions," 50; Matthäus, *BKMK*, 142, no. 167, pl. 19.167; Hakulin, *BLMC*, Appendix V.2/27, no. 937.

⁵²⁸ Hakulin, *BLMC*.

⁵²⁹ Matthäus, *BKMK*, 142.

Description

The pan has a flat base, low walls and a heavily-thickened rim. A tall, cylindrical handle from the same material rises vertically from the rim, tapering from top to bottom. The base, which is cracked and had corroded away in parts, has been reconstructed with filler. There is light corrosion over the entire surface. The base was repaired in antiquity with two pieces of thin sheet riveted to the inside and outside of the wall with flush rivets.

The rim has been thickened to 5-6 mm wide, overhanging both sides of the wall but more so to the outside, and is slightly curved on the upper edge. The hollow handle is formed from a wedge-shaped piece of sheet rolled into a tapered tube, the edges meeting behind (**figure 205**). The top edge of the sheet is 1.2-1.5 mm thick and is splayed slightly outwards. At the bottom end of the handle, the sheet thins to 0.5 mm thick. Where the handle rises from the rim, the rim is carefully shaped at the back so that the thick rim material transitions into the sheet from which the handle is made.

Cracks in the vessel reveal the material thickness at various points. Halfway down the wall, the material thins to 0.5-0.6 mm thick and thins further to 0.3 mm where the wall curves in to the base. The material is 0.25-0.3 mm thick 50 mm from the centre of the base. The pieces of sheet used for the repair are approximately 40 by 10 mm. Where some of the rivets of the repair are missing, the holes are 1.5-2 mm in diameter (**figure 206**).

Method of Construction

As for the other pan of this type (§6.1.7), this was made from a billet with a bar extending from its edge as a provision for hammering the handle. The disc of the billet was hammered thin and concave, the wall raised, and the base hammered flat. The rim was caulked between rounds. The handle provision was subsequently forged into sheet and rolled around a mandrel. Particular attention was paid to hammering the shoulders on either side of the handle to a smooth transition.

§6.1.9. Hydria (Figures 207, 208 and 209)⁵³⁰

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M12
BKMK Type	21
BKMK no.	238
Dimensions	h. 438-440, rim diam. 135-139, base diam. 180 ⁵³¹
Appendix 1 no.	181

Description

The hydria is piriform with a bulge around the base. The rim is folded out. A strap-handle extends horizontally from the rim and bends down to the top of the shoulder. A horizontal loop-handle sits further down the wall below the shoulder. There is a tear in the sheet where the rim folds out and a large piece of sheet is missing from the base section on the wall. There is mild corrosion over the surface.

The body is made from four sections joined along each of the three seams with a row of rivets: the top section, shoulder section, middle section and base section (**figures 210 and 211**). The uppermost seam is just below the neck, on top of the shoulder; the middle seam is just below the shoulder, and the bottom seam is approximately halfway between the middle seam and the base. There are no vertical seams. The top section overlaps the top edge of the shoulder section by 40 mm and is attached with a row of flush rivets with outside diameters of 6 mm set 25 mm apart. The middle section overlaps the bottom edge of the shoulder section by 30 mm and is attached here by a row of rivets with outside diameters of 6 mm set 25 mm apart. The base section overlaps the bottom edge of the middle section by 90 mm and is attached here by a row of rivets with outside head diameters of 4 mm set approximately 25 mm apart. The 90 mm underlap of the middle section extends down inside the vessel to just above the bulge of the base. Near the bottom edge of this section, there is a row of rivets on the inside of the vessel, but they do not come through to the outside (**figure 212**). The base must have been replaced, which also explains why the rivets in the bottom row have

⁵³⁰ Matz, *Forschungen auf Kreta*, 73, no. M 12 and pl. 57.1; Catling, *CBMW*, 176, no. 12.7; Matthäus, *BKMK*, 172, no. 238, pl. 29.238; Hakulin, *BLMC*, Appendix V.2/27, no. 866.

⁵³¹ Matthäus, *BKMK*, 172.

different head-diameters from those in the two upper rows. The original base was much shorter than the replacement base.

All of the outer-rivet heads of the seams are flush-type, protruding above the sheet between nil to 1 mm. The inside heads had been flattened but are not completely flush. Where sheet is missing from the base section, a hole for an absent rivet is approximately 2.5 mm in diameter, indicating that this was the shaft diameter of the rivets in the bottom row. This hole appears to have been created by puncturing the sheet from the outside, since the hole flanges toward the inside.

The material thickness at the edge of the rim is 1.2 mm. At the bottom edge of the top section, it is 1 mm, at the top edge of the middle section 0.7-1 mm, and at the top edge of the base section 0.7-1 mm. At the tear between the neck and the rim it is 0.7 mm and where the large piece of sheet is missing from the bottom section it is fairly uniformly 0.7 mm along the profile.

The upper handle is trapezoidal to D-shaped in section and tapers from top to bottom (**figures 213 and 214**). A double-lobed flange at the upper end is attached underneath the rim with two mushroom rivets. The bulbous heads are on the upper side of the rim with diameters of 15 mm and are 4-5 mm high in the centre. The flush heads are 6 mm in diameter, protruding 1-2 mm above the surface. The bottom end of the handle is attached to the top of the shoulder by one flush rivet 6 mm across on the outside. The inner-head of this rivet, which could be examined only by touch, seemed to be significantly larger than the outer, perhaps up to 15 mm in diameter and protruding 2 mm. At the centre-top of this handle, adjacent to the rim, there is a small knob 6 mm in diameter protruding 3 mm, which was probably an aid for gripping the handle.

The lower, horizontal loop-handle is approximately 12 mm square in section and has downwardly orientated vertical attachment-plates fixed to the wall with one flush rivet per plate (**figure 215**). The outer-head diameters are 7 and 10 mm protruding 1 mm and the inner-heads, accessible only by touch, are approximately 15 mm in diameter, protruding 1 mm.

There are raising marks on the vessel wall on the bottom section (**figure 216**) and also on the neck. The relatively sparse distribution of these indicates that they may have occurred during a repair rather than during the vessel's construction. That they are not found consistently over the entire surface also reflects this. The shoulder was repaired at some stage. It must have been dented. This was repaired by pushing it back out from

the inside, leaving a patch of smaller dents which are typical of this type of repair (figure 217). These repairs may be ancient or modern.

Method of Construction

The four sections of the body were hammered separately and the handles made by lost-wax casting. For the base section, the billet was hammered thin and concave, the walls raised and the base flattened. The base-bulge was incorporated into the raising rounds or made afterwards with localised sinking at the base. The top, shoulder and middle sections are open at each end. The bottom edge of the middle section, which is inside the vessel just above the base-bulge, has a rough and lumpy appearance which may have remained after the base of this section was cut off with a chisel (figure 212).

The middle section was made in the same manner as the base section, except for the base-bulge, and the base was cut out after preliminary shaping.

The shoulder section was made upside-down. The billet was hammered thin and concave to make a large bowl. The walls were subsequently raised up and slightly in, and a hole cut in the base of the bowl, the edge of which was hammered out to form the base of the neck.

The top section was made by hammering the billet thin and concave and the walls were raised to vertical. The base was subsequently removed and the wall around the hole hammered to flare out to join the shoulder. The rim was caulked and folded over.

In order to join the sections together, the order in which the holes were made would have been carefully planned. Along a seam, to ensure that the holes on the inner and outer sections were perfectly aligned, the holes on the outer section were probably made first, the two sections placed in their final position, and then the holes on the inner section were made through the holes of the outer section. To prevent the pieces from moving during the forming of later holes, the first hole and some other of the initial holes would have had their rivets threaded through to hold the pieces together. In order to ensure that the seam would sit evenly around the circumference, after the first rivet is placed, the second might be fixed on the opposite side of the vessel, the third halfway between the two and the fourth opposite the third. Otherwise, the sections could end up sitting askew. The large overlap on all of the seams would have simplified the task of aligning the sections.

The order in which the hydria sections were joined would be planned so that the seams would all be readily accessed from both sides, as well as the rivets of the handles. The simplest method would have been first to join the top section to the shoulder

section and the base section to the middle section, attach the handles, and join the central seam last, since this would be the least difficult to reach through the mouth of the hydria. During or after hammering the rivet-heads flat, the overlaps of the sections were also hammered.

§6.1.10. One-Handled Basin (1) (Figures 218, 219 and 220)⁵³²

Period	Unspecified LM ⁵³³ or LM III ⁵³⁴
Site	Piskokephalo
Collection	ANM 54
BKMK Type	32A
BKMK no.	311
Dimensions	h. 70-77, rim diam. 330, base diam. 150-160 ⁵³⁵
Appendix 1 no.	117

Description

The basin is broad and shallow, curving to a dropped foot. The heavily-thickened rim overhangs both sides of the wall. The strap-handle is an extension of the basin material, and extends up and out from the rim in a circular loop, its end not quite touching the lower wall of the basin and tapering from the rim to the tip. The handle is decorated on the outer surface with a raised central ridge with three intaglio lines on either side of it. Most of the foot and parts of the wall have disintegrated and have been reconstructed with a waxy substance. Part of the rim is missing. The surface is heavily corroded and is blistered and layered in parts. Where the metal surface is visible, the colour indicates that it is bronze.

The rim is heavily caulked to 9-10 mm wide, the upper surface angled slightly down to the outside (figure 221). Where parts of the rim have corroded away, the upper edge of the wall immediately under the rim is 2.5 mm thick. A break between the extant material and the reconstruction on the foot reveals the material at the point where the wall ends and the dropped foot begins to be 1 mm thick. The foot has an inside diameter of 145 mm and drops 10 mm.

⁵³² S. Marinatos, "Ausgrabungen und Funde auf Kreta 1936/37," *Archäologischer Anzeiger* (1937): 224; Matthäus, *BKMK*, 207 no. 311, pl. 37.311; Hakulin, *BLMC*, Appendix V.2/27, no. 930.

⁵³³ Hakulin, *BLMC*.

⁵³⁴ Ayios Nikolaos Archaeological Museum case label.

⁵³⁵ Matthäus, *BKMK*.

Where the handle rises from the rim of the basin it is 80 mm wide and tapers along its length to 40 mm at its end near the outside of the wall. The handle thickness varies between 2 and 3 mm. There is a smooth transition between the caulked rim and the sides of the handle (**figure 222**). The back surface of the handle, on the obverse of the decorated side, has no marks corresponding to the decoration.

Method of Construction

The handle-decoration indicates that the basin was hammered from a billet made by lost-wax casting. Since there are no marks on the underside of the handle corresponding to the decoration on the outside, chasing can be ruled out, since this would cause deformation on the underside. We must also rule out engraving, since there were no available materials capable of cutting into the surface of the material (see §4.6.3). The decoration must have been carved into wax for lost-wax casting.

The changes in material thickness, however, make it clear that the vessel was definitely not cast in its final form. The material thickness of 1 mm near the foot is too thin to have been cast, and the change from thicker material underneath the caulked rim to thinner material at the base is characteristic of sinking or spiral-forging, whereby the rim remains thick in comparison to the centre, or base.

The handle could not have been hammered into shape after it was cast since this would have damaged the decoration. The handle must be the same thickness now, 2-3 mm, as it was upon casting. From this one might extrapolate that the entire billet was probably a similar thickness. The material thickness of 2.5 mm under the rim corresponds to this. The handle was probably cast flat, because it would be cumbersome to hammer the basin with the handle in the way.

The wax blank of the billet was shaped and the decoration carved into the wax for the handle. After casting, the disc was hammered thin and concave, and the rim caulked between rounds. Due to the roundness of the profile, raising may not have been required to bring up the walls. When the desired depth was achieved, the foot was sunk. The handle was then bent into shape, perhaps by hand over a mandrel, and the rim caulking finished, with careful modelling of the transition from rim to handle.

§6.1.11. One-Handled Basin (2)⁵³⁶

Period	unknown
Site	Palaikastro
Collection	BSA no. PK 03/8053, cat. no. 8053, zembil no. 4909
BKMK Type	*32A
BKMK no.	n/a
Dimensions	total h. 90, body h. 53-75, rim diam. 235-250, base diam. 120-130 ⁵³⁷
Appendix 1 no.	237

Description

Due to corrosion which has destroyed the rim and the base of the vessel and the subsequent modern reconstruction, some features are obscured. However, the shape corresponds closely to the one-handled basin above (§6.1.10), though it is smaller and the handle is not decorated. It has a large, round basin, a dropped foot, a tapering strap handle with a circular profile made from the same material, and a heavily thickened rim which originally overhung the inside and outside of the vessel. The metal is bloated from corrosion. Where corrosion has been cleaned away, the material is a bronze colour.

Although the rim has mostly corroded away, the remaining material here, thickening substantially at the top edge, indicates that it had been heavily thickened in the same manner as the previous basin described. There was also a smooth transition from the rim to the edges of the handle. Because of the bloating caused by corrosion, it is difficult to conclude anything about material thickness over most of the vessel, but the caulked rim was approximately 10 mm wide, and the wall immediately under it 1.5 mm. A crack in the wall 40 mm from the rim reveals the material thickness to be 1 mm. The internal diameter of the dropped base is 120-130 mm, but its height is unknown, since it has corroded away. The reconstructed foot height of 7-8 mm is probably accurate.

The handle is in relatively good condition, and where the material is not too bloated, the original thickness appears to have varied from 1 to 2 mm. Where it rises from the rim, the handle is 50 mm wide, tapering at its tip near the wall to 21 mm.

⁵³⁶ Unpublished, to my knowledge. Refer to images of the previous one-handled basin, §6.1.10.

⁵³⁷ My measurements.

Method of Construction

The basin was hammered thin and concave from a billet with provision for the handle, but due to the thinness of the material (1-2 mm on the handle), it is likely that the billet was cast thicker than the final thickness of the handle and the handle forged out somewhat. The basin was shaped and the rim caulked throughout the process. The rim was finished, then the dropped foot made, the handle was bent into shape, probably by hand, and the rim and handle-edge transition caulked.

§6.1.12. One-Handled Cup with Dropped Base (Figures 223 and 224)⁵³⁸

Period	LM I-III A ⁵³⁹
Site	unknown
Collection	CM M64 (Mitsotakis Collection)
BKMK Type	*33
BKMK no.	n/a
Dimensions	total h. 52, rim diam. 122-131, base diam. 55 ⁵⁴⁰
Appendix 1 no.	187

Description

A one-handled cup of one piece of metal. The strip handle extends vertically from the rim, loops down and is fixed to the wall near the base with a single rivet. The foot is dropped. Other than some mild corrosion over the surface, the cup is in good condition. The surface has scratches on it from modern corrosion removal and has been sealed with a lacquer. The colour of the material indicates that it is bronze.

The rim of the vessel is uneven, and has been lightly thickened to 1-1.5 mm. The handle gradually tapers in along its length before splaying out at the end, where it is attached to the wall with a rivet (**figure 225**). At the top of the loop, the handle is 0.9-1 mm thick, and thickens along its length to 1.2 mm where it is attached to the cup. The rivet used to attach the end is not a piece of wire or rod as is usual, but a small strip of sheet 5 by 10 mm and 1.2 mm thick. The holes through which the rivet is inserted are slits rather than the usual round holes. The heads of the rivet are not flattened on the ends but splayed, and the rivet sits diagonally through the slits rather than travelling

⁵³⁸ Tsipopoulou, "Minoan Metal Vases and Vessels," 235, no. 302.

⁵³⁹ Ibid.

⁵⁴⁰ Ibid.

through perpendicular to the surfaces, which has fixed the handle askew. At the slit in the wall, 30 to 45 mm from the rim, the material thickness is 0.4-0.5 mm.

The dropped foot is not quite round, but varies between 60 and 65 mm in diameter at the top and 53 and 55 mm at the base. Its edges have not been sharply defined, but are rather curved. A point has been punched in the centre of the dropped base on the inside of the vessel and a line inscribed in a circle around the point (**figure 226**). These would have been reference-lines for keeping the cup and the dropped foot symmetrical. However, the inscribed line has not been followed, and does not correspond to the final shaping of the foot. The profile of the cup is also uneven, more so than is usual for Minoan vessels. Where the rivet has been attached, the wall is flat, a result of hammering the rivet ends without an appropriately-shaped working surface underneath.

There are many technical features of this cup which are unusual in Minoan vessels. The rim is uneven and not well reinforced. The profile, foot and handle are uneven. The rivet is of sheet rather than rod and is set through a slit rather than a hole. The circumference of the cup is askew, but this could be a result of damage after its deposition. This vessel must have been made by an inexperienced smith.

Method of Construction

The cup was made from a billet with a rod-type provision for the handle extending from its edge. The bowl and foot of the cup were formed entirely by sinking or spiral-forging, and the handle provision subsequently forged flat and bent by hand.

§6.1.13. Beaker with Spout (Figures 227 and 228)⁵⁴¹

Period	LM IIIB ⁵⁴²
Site	unknown
Collection	CM M62 (Mitsotakis Collection)
BKMK Type	*40
BKMK no.	n/a
Dimensions	h. 85, base diam. 97 ⁵⁴³
Appendix 1 no.	212

⁵⁴¹ Ibid., 241, no. 308.

⁵⁴² Ibid.

⁵⁴³ Ibid., 241.

Description

This beaker has a flat base, and the wall circumference narrows in the middle and expands out towards the rim, forming a waist. The rim is thickened. There is a horizontal spout of the same piece of material as the body, and a single handle opposite the spout of a separate piece. The handle extends out from just below the rim and loops back in to the wall a quarter of the way down the side. There is mild corrosion over the surface and tears in the rim on either side of the spout. Scratches on the surface are from modern corrosion removal, and lacquer has been applied over the surface. Where the metal is exposed, the colour indicates that it is bronze.

The rim is thickened to 3 mm wide at its greatest width down to 2 mm either side of the spout, where the thickening ends (**figure 229**). The rim overhangs the inside by 0.25 mm and the outside by 1.5-2 mm and is angled out and down. The spout has a flat bottom and straight sides, and there is a sharp fold in the vessel wall where the spout enters. The rim narrows to 0.7 along the length of the spout. The bottom edge of the end of the spout is 0.5 mm thick.

The handle is a piece of sheet in a T-shape (**figure 230**). The top of the T is attached just under the rim with two flush rivets. The diameters are 4-5 mm on both sides. The band of the handle is curved up and loops back down and in to the wall, where it is attached with one flush rivet the same size as the other two. On the loop of the handle, the sheet is 1.75 mm. Where it meets the rim, it thins to 1 mm, and at the bottom it thins to 0.8 mm at the edges.

Method of Construction

The billet had a tab on its rim as provision for the spout. The disc was hammered thin and concave, the walls raised and the base flattened. The middle of the wall was raised in further than the rim to create the waist. The tab on the rim was forged into sheet and sunk, and the rim caulked. A small billet was forged out into sheet for the handle. The T-shape may have been forged out or cut from larger sheet. It was bent into shape by hand.

§6.1.14. Kalathos or Lekane (Figure 231 and 232)⁵⁴⁴

Period	LM IIIA-B ⁵⁴⁵
Site	unknown
Collection	CM M60 (Mitsotakis Collection)
BKMK Type	*45A1
BKMK no.	n/a
Dimensions	h. 135, rim diam. 291, base diam. 173 ⁵⁴⁶
Appendix 1 no.	207

Description

This kalathos, as it is referred to by Tsipopoulou, or lekane, as it fits into Matthäus' typology, has a narrow, flat base and its walls narrow further to a waist before expanding out to a large rim. The rim is heavily thickened with two horizontal loop-handles attached underneath. It is in excellent condition with no breaks in the material. There is minimal corrosion over the surface, and it has been sealed with lacquer. Where the metal is visible, the colour indicates that the body is bronze.

The rim is heavily caulked with a curved upper surface angled out and down (**figure 233**). It is 11-12 mm wide, overhanging the inside by 1.2 mm and the outside by 4 mm. Since the vessel is in such excellent condition, it is not possible to observe the material thickness on any part of the body.

The handles are round in section with large, round-cornered, triangular attachment-plates (**figure 234**). Each plate is attached to the wall with three mushroom rivets, the bulging head on the inside (**figure 232**). The outer-head diameters vary between 3 and 4 mm and the inner diameters are 15 mm. Bubbles in both handles indicate that they were cast. Furthermore, the location of some of the bubbles on one attachment-plate, around the hole where a rivet passes through, indicates that the handle was cast with the holes for the rivets in place (**figure 235**). They would have been bored through the wax made for the cast.

Method of Construction

The thickness of the rim suggests that a thick billet may have been used, perhaps up to 5 mm. The billet was made thin and concave and the walls raised up and in. The waist

⁵⁴⁴ Ibid., 236, no. 304.

⁵⁴⁵ Ibid.

⁵⁴⁶ Ibid., 236.

was formed by raising in the lower-third further than the upper wall and the base was hammered flat. The rim was caulked between shaping rounds and after, and the handles made by lost-wax casting.

§6.1.15. Lekane with Handles and Spout (Figures 236, 237 and 238)⁵⁴⁷

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M115
BKMK Type	45B2
BKMK no.	403
Dimensions	h. 150, rim diam. 199-203, base diam. 114 ⁵⁴⁸
Appendix 1 no.	162

Description

Lekane with flat, narrow base and walls curving out to the rim. There are two wishbone handles on opposite sides of the vessel. The spout, halfway between the handles, is of the same piece of material as the body. The rim is thickened, overhanging both sides of the wall, and has a curved upper surface angled slightly out and down. There is light oxide over the entire surface, but other than some corrosion holes around the outside of the base, small tears on either side of the rim and a piece missing at the end of the spout, the vessel is in excellent condition. Horizontal scratches around the surface are from modern corrosion removal. The colour of the material indicates that the body is bronze.

The rim is 5 mm wide and overhangs the inside and outside of the wall by 1.5 mm on either side. The thickening narrows and ends on either side of the spout, the rims of which are folded out (**figure 239**). The profile of the spout is a shallow semi-circle. The end of the spout is 0.6-0.7 mm thick and at the corroded holes around the outside of the base the wall is 1-1.1 mm thick.

The handles are attached to the wall with one rivet per attachment-plate. One of the handles came off the vessel and was re-attached in antiquity. This is suggested by the presence of outer rivet-heads on one handle but not the other (**figures 240 and 241**). This indicates that the handles were originally cast with rivet-shafts protruding on the undersides of the attachment-plates. On one handle, one or both of these shafts broke,

⁵⁴⁷ Matz, *Forschungen auf Kreta*, 73, no. M 115, pl. 57.2; Catling, *CBMW*, 172, no. 6c.6; Matthäus, *BKMK*, 267, no. 403, pl. 48.403; Hakulin, *BLMC*, Appendix V.2/27, no. 864.

⁵⁴⁸ Matthäus, *BKMK*, 267.

and, to re-attach the handle, holes had to be made in the attachment-plates so that new rivets could be inserted. This repaired handle was apparently not attached very competently, because the wall material around the attachment-plates buckled, leaving the attachment-plates and the new rivet-heads protruding at angles.

Method of Construction

The billet had a provision on its rim for the spout. The disc was hammered thin and concave, the wall raised and the base hammered flat. The rim was caulked between shaping rounds and after. The spout-provision was forged out and shaped and the handles were made by lost-wax casting.

§6.1.16. Straight-Walled Bowl with Dropped Foot (Figures 242 and 243)⁵⁴⁹

Period	LM IIIA1
Site	Chania, tomb south of the law-courts
Collection	CM M114
BKMK Type	50
BKMK no.	430
Dimensions	h. 52-54, rim diam. 222-225, base diam. 106 ⁵⁵⁰
Appendix 1 no.	166

Description

Straight-walled bowl with a thickened rim and dropped foot. There is a moderate amount of corrosion over its surface and parts of the vessel where the wall meets the base have corrosion-holes.

The rim was thickened to 2.5-3 mm, and thins to the average wall-thickness after 5 mm. Holes where the wall meets the base reveal the material thickness here to be 0.5-0.6 mm.

⁵⁴⁹ Matz, *Forschungen auf Kreta*, 73, no. M 114; Matthäus, *BKMK*, 285, no. 430, pl. 50.430; Hakulin, *BLMC*, Appendix V.2/27, no. 865.

⁵⁵⁰ Matthäus, *BKMK*, 285.

Method of Construction

The billet was hammered thin and concave, the base hammered flat and the walls raised. The rim was caulked between shaping rounds. Subsequently, the foot was dropped by sinking.

§6.1.17. Ladle with Dropped Base (Figures 244 and 245)⁵⁵¹

Period	LM IIIB ⁵⁵²
Site	unknown
Collection	CM M63 (Mitsotakis Collection)
BKMK Type	*57C2
BKMK no.	n/a
Dimensions	total h. 107, body h. 30, rim diam. 94 ⁵⁵³
Appendix 1 no.	213

Description

Small ladle with an everted rim and a dropped base. The handle is an extension of the body, rising diagonally from the rim and with a loop at the top. There is light corrosion over its surface and a section of the rim and upper wall is missing on one side. There are scratches over the surface from modern corrosion removal and it has been sealed with lacquer. The colour indicates that it is made of bronze.

The lip on the rim is 4-5 mm wide and 1 mm thick at the edge. Where it folds out from the wall, the material is 0.9 mm thick and thins further down the wall to 0.7 mm at 8 mm from the lip and 0.5 at 16 mm from the lip. The handle is a thin strip, varying between 1 and 1.2 mm thick. It rises up from the rim, forming a loop at the top, and doubles back on itself. The end, which is 0.8-0.9 mm thick, is attached to the bowl with a single, flush-head rivet with an inside-head diameter of 5 mm and outside of 4.5 mm. Behind the rim where the tear is, there is a patch made from a small piece of sheet 0.9 mm thick attached with one flush rivet on each end. The foot drops 4 mm and is 49-50 mm in diameter at the top and 45-47 mm at the base. A punched point in the centre of the base served as a guide during manufacture (figure 245).

⁵⁵¹ Tsipopoulou, "Minoan Metal Vases and Vessels," 240, no. 307.

⁵⁵² Ibid.

⁵⁵³ Ibid.

Method of Construction

The small size and thin material of the ladle indicate that it was made from a small billet with a provision for the handle extending from the edge. Since the material is so thin and the vessel so small, the billet was probably forged into sheet first. The bowl was then shaped by sinking. It is unlikely that raising would be carried out on such a small, simple vessel. The rim was subsequently hammered out and the handle provision forged into a strip and bent into shape by hand.

§6.2. Summary of the Findings from the Vessel Examinations

These examinations have revealed several techniques used in the manufacture of Minoan vessels. The construction of the one-handled basin from Piskokephalo (§6.1.10) demonstrates that, at least on some occasions, billets were made by lost-wax casting. This would allow for complex billets with edge-provisions for spouts and handles to be created easily, and may explain why so few stone moulds for discs are extant. The nature of lost-wax casting, with the mould being broken, means that these moulds are less likely to survive. It is interesting that the billet for the one-handled basin may have been as thin as 2.5-3 mm, since achieving such a thin cast would be quite difficult.

The handles on the Chania lekane (§6.1.15) seem to have originally been made with the rivet shafts incorporated into the cast handle. A technique such as this would eliminate the need to make a hole in the thick material of the attachment plates, which would have been difficult to do without altering the shape of the plate, since, as was discussed in §4.6.2, it is unlikely that Minoan smiths could drill through bronze. The alternative, using punches, causes a fair amount of material displacement. Another technique used to avoid this problem, which is apparent on the kalathos/lekane in the Mitsotakis Collection (§6.1.14), was casting the handles with the holes already in place.

The manner in which holes were made in sheet has been illuminated somewhat by the presence of flared holes for rivets on some vessels including the Chania hydria (§6.1.9) and the two-handled basin in the Ashmolean collection (§6.1.6). These seem to confirm that holes were made by punching through the material with a sharp tool. However, many of the holes on the vessels were flat, and the material which would be left from punching through the sheet (the flare) is absent.. This may indicate the use of a

technique such as that described by Rostoker,⁵⁵⁴ which creates an open, smooth-edged hole (§4.6.2). Another possibility is that the holes were punched and the flare cut back with abrasives.

Several overall observations on Minoan vessel-making techniques can be made. The material was frequently worked very thin, often as thin as 0.5 mm, and sometimes thinner. This is far thinner than in modern metalsmithing, where material less than approximately 0.9 mm is avoided since it tends to be difficult to control its movement during hammering. The Minoan practice no doubt reflects the high value of the material. Such thin fabric would have been problematic for copper vessels, since it is so soft and therefore vulnerable to denting, but it was probably suitable for bronze.

Practically all of the vessels examined had thickened rims, even when another rim-reinforcing method such as folding was used. Caulking not only thickens a rim, but also straightens it. The forming processes, particularly raising, usually create a ragged rim, but caulking it between rounds keeps the rim relatively even. This probably explains why thickened rims are so commonly found on the Minoan vessels.

None of the vessels show any of the surface marks characteristic of planishing: faceting on the outer surface or dimpling on the inner surface. This seems to confirm the observations in Chapter 4 (§4.5.1) that planishing was probably not used owing to the rarity of metal tools. Burnishing may have been used instead to smooth the vessel surface. It was not possible to observe the degree of finish on the surfaces of the vessels because of the corrosion over the surfaces and also because of the presence of scratches from modern corrosion removal which obscure the original surface marks.

The hydria (§6.1.9) is clearly the most complex of Minoan vessels. It required the use of almost all of the vessel-making techniques in the tradition as well as careful design and planning to fit the sections together. Therefore, their manufacture was probably limited to smiths with a fair amount of experience. Since they required a relatively large amount of material and required so much skill to piece together, the task would probably not have been trusted to less-experienced smiths. These factors must also have made them rather valuable. Some other vessels, however, such as the one-handled cup in the Mitsotakis Collection (§6.1.12), are reasonably simple and would be a suitable beginner's project, incorporating casting, basic shaping, hole-making and riveting. Likewise, two-handled basins (§6.1.6) represent the most basic techniques. Many of the other vessels examined, tripod cauldrons, pans with hollow, vertical

⁵⁵⁴ Rostoker, "Ancient Techniques for Making Holes in Metal Sheet."

handles, one-handled basins, spouted vessels and lekanai, might be considered intermediate projects, requiring casting, basic shaping, raising to varying degrees of complexity, careful caulking and forging, hole-making and riveting.

I believe that the above observations can be applied to most vessels in the Minoan corpus, since this selection represents variations on most of the forms. With such a small sample, however, and most of it limited to after the Neopalatial period, it is impossible to make any observations on chronological differences in techniques. Likewise, the fact that several of the vessels are not provenanced prevents any observations on geographical variations. It would also be useful to examine some of the vessels which have been posited as having been cast, or of casting having played a large part in their construction (§3.2 and 3.3). Metallographic analyses of some vessels would also illuminate some of the metalworking processes, particularly on vessels thought to have been cast.

We have now established the range and features of the vessel corpus, the basic steps required to make metal vessels whether ancient or modern, previous theories about how they were made, archaeological evidence for Minoan metalsmithing technology, and the evidence from the vessels themselves. The next step is to test the findings with practical application in a metalsmithing workshop. This is the topic of the next chapter.

Experimental Reconstruction of Minoan Vessel-Making Processes

We have now analysed the available evidence for the equipment and techniques used to make Minoan vessels. The final stage is to examine aspects which can only be investigated by applying this equipment and these techniques practically in experimental reconstruction.

Several stages of the vessel-making process are already well established by previous research and it is unnecessary to test these. Van Lokeren has already dealt with how ingots were broken apart (see §4.2.1),⁵⁵⁵ and it is generally agreed that billets were cast with ceramic crucibles in open and closed stone moulds and lost-wax moulds with bellows for artificial draught (see §4.2.2).

The parts of the process which are worth testing are those which are largely unknown. Whether pi-shaped hearths may have been used for metalworking has not been established. It is not known whether stone tools extant from Minoan metallurgical sites could have been used for vessel-making or whether there is a missing class of bronze tools. Various abrasive stone tools are found at metallurgical sites; it is worth studying what role these might have played in the vessel-making process. Testing methods for cutting metal, making holes and riveting might also add something to studies of Minoan technology.

There are parts of the process which are lost to us forever. Whether oxides were removed from a metal surface and how this might have been carried out is not a process which survives in the record. In §4.3, some theories on this were discussed, but it is only possible to speculate. Likewise, it is virtually impossible to tell whether vessels were highly polished, though it is clear that the surfaces were not left untouched after the shaping processes (see §6.2). For these two processes, some practicable ideas can be tested but it would not be wise to draw conclusions.

In this chapter, brief descriptions of the vessels produced are given in the first section. In the second section, the equipment and materials used in the reconstructions are illustrated and discussed, and the third section describes how the reconstructions

⁵⁵⁵ Van Lokeren, "Experimental Reconstruction of the Casting of Copper 'Oxhide' Ingots."

were carried out. The final section discusses the findings and their implications for this study. Many of the reconstructions were filmed; these can be found in Appendix Three, the DVD accompanying this volume. The relevant chapters of Appendix Three are cited below where appropriate.

§7.1. The Vessels

Initially, two small copper bowls were made to establish methods for using the replicated tools before larger forms were made (**figures 246 and 247**). Afterwards, two Minoan vessel types were made. The first was a copper hydria similar in design and dimensions to the bronze hydria from Chania described in §6.1.9 (**figure 248**). The body consists of four sections: a base section, middle section, shoulder section and top section (**figure 249**), and there is an upper and a lower handle. The body sections were shaped by hammering. Unlike those of the Chania hydria, the handles here were forged from copper rod. The method for making handles was not tested, since most were cast. Rather, the handles were made so that the method for attaching them to the body could be investigated. The vessel-sections were joined and the handles attached with copper rivets, and the surface was finished to a high polish. A hydria was made because, as discussed in §6.2, it is the most complex in the corpus and incorporates the broadest range of techniques. By making a hydria, most of these techniques could be tested.

The second vessel of Minoan type that was produced was a sterling silver one-handled basin (**figure 250**) similar to those from Piskokephalo (§6.1.10) and Palaikastro (§6.1.11) which were examined for this study. This was made from a billet with a handle provision on the edge. After the body was formed, the handle was bent into shape and the surface polished. Sterling silver was used so that the replicated tools could be tested on a material closer to bronze in hardness than pure copper (see §7.2.1 below). This vessel also provided an opportunity to test techniques not used during the hydria's construction: hammering a billet with a handle provision, shaping a form without raising, and creating a heavily caulked rim.

In this chapter, the replicated equipment is described in detail and the techniques used are summarised to the extent necessary to draw conclusions for this study. Detailed descriptions of the techniques used to make each vessel and vessel section are given in Part Two of this study.

§7.2. Equipment and Materials

§7.2.1. Metals

Metal Hardness and the Choice of Materials for the Reconstructions

It was not possible to make the vessels and tools in alloys identical to their Minoan counterparts. The alloys used to make Minoan vessels were discussed in §1.2.3.

Overall, the analyses indicate that the favoured tin percentages for making the bodies of bronze vessels range between 1 and 12% tin. Analyses of tools from Knossos and Ayia Triada conducted by Evely and Stos indicate tin percentages of 5-9% at the start of the Neopalatial period and 10-14% during the Monopalatial period, though some tools were unalloyed.⁵⁵⁶ Analyses of rivets from the same study indicate that rivets were copper. Such tin percentages for the tools would have been chosen for their durability and their ability to maintain a sharpened edge. The rivets would have been copper because, since it is relatively soft, the rivets could easily be closed by forging.

Bronzes could not be purchased for this study because modern bronzes have other components, largely phosphor and silicon, which alter the working properties of the material to such an extent that they are no longer comparable to prehistoric bronze. I was not able to find a manufacturer willing to produce the relevant alloys and my attempts to create the alloys were unsuccessful. Consequently, it was necessary to compromise on the choice of materials. After comparing the hardness ranges of prehistoric bronzes with those of modern metals, I chose to use copper and sterling silver.

Indentation hardness tests on metals indicate the amount of plastic deformation a material undergoes for a given amount of force applied, assigning a hardness ranking in units of Hardness Vickers (HV). A metal with a low hardness measurement tends to be malleable whereas a high hardness indicates a material which is difficult to deform. A study conducted by Papadimitriou tested the cold formability of bronze alloys used in antiquity. These findings are summarised in Chart 2.

⁵⁵⁶ Evely and Stos, "Aspects of Late Minoan Metallurgy at Knossos," 267.

Chart 2. Work Hardening of Tin Bronzes

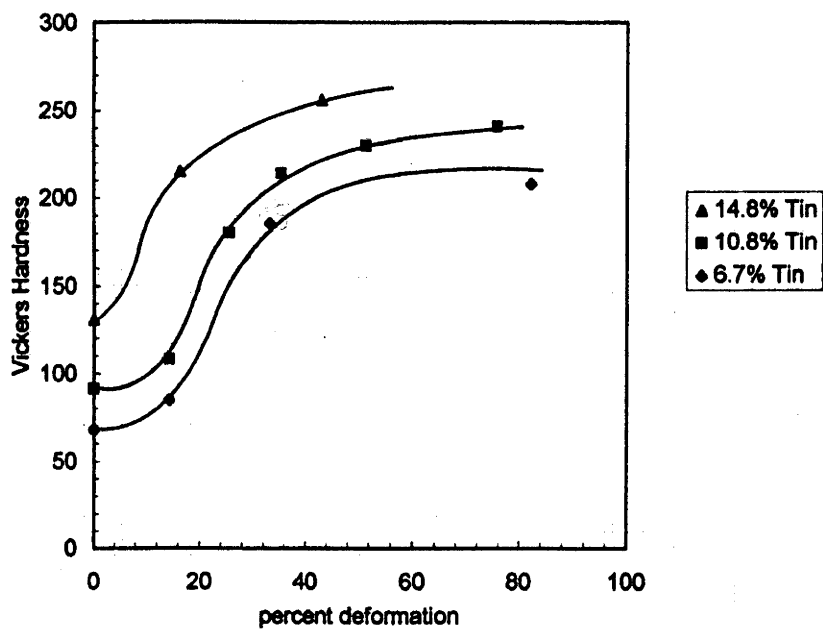


Chart 2. Changes in Hardness Vickers of bronzes with 6.7%, 10.8% and 14.8% tin which occur over increasing percentages of plastic deformation. *Source:* Papadimitriou, “Simulation Study of Ancient Bronzes,” 725, fig. 6.

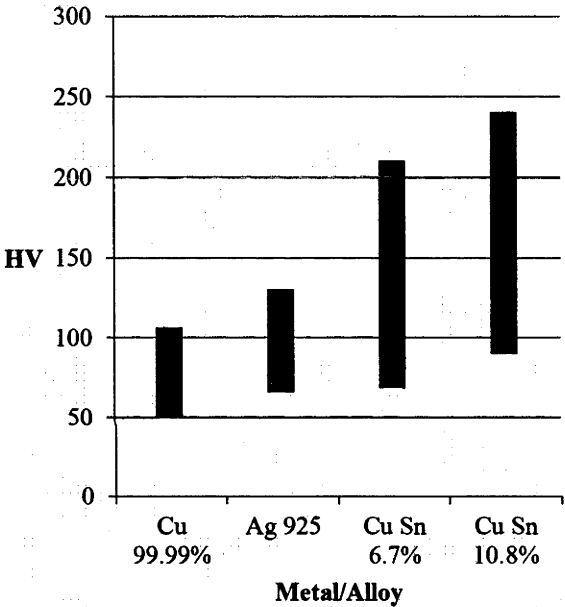
The results of the study show that an annealed, unworked bronze with 6.7% tin has an initial HV of approximately 70 and hardens to 80 after almost 20% deformation, 175 HV after 35% deformation and 200 HV after 85% deformation. Bronzes with higher tin percentages harden at similar rates but have correspondingly higher hardnesses. By comparing this data with hardness ranges of other metals, one can observe their relative workability. The data for 6.7% and 10.8% tin bronzes, which are those most relevant to this study, are listed in Table 4 alongside those of copper and sterling silver. These are compared in Chart 3.

Table 4. Hardness Ranges of Copper, Sterling Silver and Tin Bronzes

Metal/Alloy	Hardness Range (HV)
Cu 99.99%	50-106
Ag 925 ⁵⁵⁷	66-130
Cu Sn 6.7%	69-210
Cu Sn 10.8%	90-240

Table 4. *Sources:* data from C. J. Smithells, *Metals Reference Book*, 5th ed. (London: Butterworths, 1976), 1104, table; Papadimitriou, "Simulation Study of Ancient Bronzes," 725, fig. 6; Rio Grande, "Comparing Silver Hardness," <http://www.riogrande.com/help.aspx> (accessed 20 February 2012).

Chart 3. Hardness Ranges of Copper, Sterling Silver and Tin Bronzes



The lowest figure for each material indicates its hardness in an annealed, unworked state when it is at its softest and the highest figure indicates the hardness after the material has been worked up to or near the maximum extent of its workability. It is clear that the bronzes are capable of being hardened significantly more than copper and sterling silver, but in their lower ranges, before extensive work-hardening, the hardnesses are comparable. That a bronze can be hardened to such an extent does not necessarily mean that it must be worked within these higher hardness ranges. If the material is frequently annealed, the lower hardness ranges can be maintained throughout the construction phases of an item. Higher hardness ranges are more useful for a completed object: tools

⁵⁵⁷ Sterling silver.

are more durable and vessels less prone to dents. This can be exploited by working the material to the extent of its hardenability after the object is finished and no more shaping is required. If it is not annealed, it will maintain this hardness.

This comparison of hardness data shows that copper and sterling silver, which were readily available for this study, have working properties comparable to tin bronzes. Their only failing is that they cannot be hardened to such an extent. Although it is not ideal that tin bronzes could not be used, copper and silver will not provide inaccurate results.

Metals Used for the Reconstructions

Four copper billets were used to make the hydria. The first two sections, the base and middle sections, were made from disc-billets 2 mm thick, which at the time was the thickest material available. The shoulder and top sections were made from disc-billets 3 mm thick when this gauge became available. This 3 mm plate was preferred since it matched the thickness of the billet used to make the one-handled basin from Piskokephalo (§6.1.10), which is probably the thinnest that Minoan smiths could cast in a large billet. The rivets used to join the vessel sections and the handles were also of unalloyed copper. The body-rivets were made from round rod 4 mm in diameter and the handle-rivets 6 mm.

The one-handled basin was made from sterling silver. The billet, which included the handle, pre-formed, was 3mm thick, as for the last two hydria sections. This was the maximum thickness of silver available to me.

A chisel and a punch were made from sterling silver since it would be necessary for these tools to maintain the sharpness of their working ends for as long as possible to reduce the number of times they would need to be resharpened. They were work-hardened by hammering. Both of these tools are discussed in further detail below.

§7.2.2. Hearth and Fuel (Figure 251)

The hearth was designed to replicate the hearth in Pillar Hall H of the Unexplored Mansion at Knossos (see §4.2.2 and §5.2). It did not seem necessary to replicate the materials used to make it since the only function of the structure was to contain the fuel, and the materials would have had no effect on the process.⁵⁵⁸ The walls of the

⁵⁵⁸ Unlike a smelting furnace in which the composition of the furnace material affects the chemical composition of the smelt.

replicated hearth were built on earth with refractory bricks and a scoop was dug into the soil between them. The dimensions of the hearth were 350 mm wide, 460 mm deep and 200 mm high. The exact dimensions of the Unexplored Mansion hearth (400 x 550 x 200 mm) were not replicated since the vessel being annealed did not require such a size. Charcoal from an unknown timber was used for fuel.⁵⁵⁹ Charcoal analyses from hearths at Mochlos indicate that olive timber was a common hearth fuel (§4.2.2).⁵⁶⁰ The choice of charcoal in an annealing hearth would have almost no effect on the results since the temperatures required are relatively low.

§7.2.3. Blowpipe

In lieu of a blowpipe of the correct materials, hollow reed with a clay nozzle (§4.2.2), an aluminium tube 620 mm long with an inside diameter of 7 mm was used. The internal diameter was based on data from Rehder indicating that a nozzle for a blowpipe must have an internal diameter of 5-10 mm.⁵⁶¹ The length was required to reduce facial exposure to the heat of the fire. The choice of material for the blowpipe would have no effect on the results.

§7.2.4. Pickle

In §4.3, it was noted that the manner in which oxides may have been removed from metals after annealing is unknown, although some possibilities were presented. In the reconstructions, a solution of salt and vinegar was used as a pickle.

§7.2.5. Hammers

The hammering tools found at Minoan metallurgical sites, discussed in §4.4.1, are predominantly cobbles and oblong or pestle shapes of sandstone, limestone, and igneous stones, especially fine-grained igneous stones such as andesite. The stone hammers replicated for this study were a cobblestone of basalt, pestles of marble and granite, and an oblong, fine-grained igneous stone (**figure 252**). The cobblestone and oblong stone were used in their natural state and the pestles were purchased kitchen pestles. I am not aware of any Minoan hammer-stones made from basalt or granite, but basalt, being a

⁵⁵⁹ It is probable that the charcoal was made from mangrove timber, since this is a common source of charcoal in Australia. The charcoal used was pure, unprocessed and free from accelerants.

⁵⁶⁰ Schoch and Ntinou, "Wood Charcoal," 134.

⁵⁶¹ Rehder, "Blowpipes versus Bellows in Ancient Metallurgy," 349.

fine-grained igneous rock, has a similar durability to andesite. Granite shares this durability but, being coarse-grained, is probably liable to fracture more easily. The igneous oblong stone is similar in composition to andesite, and thus a reasonably accurate replica.

Wooden hammers were replicated after two of the prehistoric wooden hammers discussed in §4.4.1: the New Kingdom Egyptian mallet and the hammer type from Neolithic Meare Heath and Bronze Age Flag Fen. It was deemed unnecessary to test the design of the mallet from the Iron Age Breidden Hill Fort since these are still used for metalsmithing today. The replicated Egyptian mallet is a modern carver's mallet of beech (*Fagus sylvatica*) (**figure 253**). The replicated Flag Fen hammer was made from an oak branch (*Quercus robur*) (**figure 254**). Beech was probably unknown in Crete, given the tree's preference for cooler climates, but it is similar in durability to oak, varieties of which grew on Crete during the Bronze Age.⁵⁶²

§7.2.6. Hollows

Several hollows were carved into the end grain of wooden stumps. These were carved during the process as required. One of these had a diameter very large relative to its depth (185x26 mm) (**figure 255**). The others were all carved according to the shape of the particular hammer being used at the time. It was found that the ideal dimensions of a hollow used for stretching material are slightly larger than the hammer face (**figure 256**).

§7.2.7. Stake (Figure 257)

The stake used for raising was carved from hardwood. It does not replicate any Minoan artefact, since nothing of this type is extant (see §4.4.2), but seemed a reasonable choice given the long history of such stakes for vessel-making. As was discussed in §4.4.2, it is impossible to know the manner in which stakes were secured for working on since we do not know what forms the stakes themselves took. Therefore, rather than attempting to test hypothetical methods which would have endless variables, this issue has not been approached here. Instead, the stake was simply fixed in a vice as per modern practice.

⁵⁶² Schoch and Ntinou, "Wood Charcoal," 135.

§7.2.8. Anvil (Figure 258)

A large piece of limestone was used as an anvil because the few Minoan artefacts which are considered anvils are of limestone (see §4.4.2). This rock was chosen because it has useful flat surfaces.

§7.2.9. Chisel (Figure 259)

A chisel with a curved, flared cutting-face was forged from sterling silver, replicating a chisel from Psychro (see §4.6.3).⁵⁶³ The Psychro chisel is 107 mm long and 7 mm in diameter with a cutting-face width of 13 mm and the replicated chisel 80 mm long and 7-8 mm in diameter with a cutting-face width of 15 mm. Another chisel with a flat cutting-face, a butt-chisel, was also made in mild steel during testing stages. Several Minoan chisels have such a shape. A sterling silver butt chisel was not made because this type was found to be unsuitable for the vessel-making process (see §7.3.4 below).

§7.2.10. Punch (Figure 260)

A sharp-pointed punch was made from sterling silver. It does not replicate any specific Minoan artefact but would have served the same purposes as the various Minoan bronze awls, points and punches which Evely lists.⁵⁶⁴ The silver punch was made with a butt-end to strike with a hammer, but the Minoan equivalents seem mostly to have had a tang, indicating that they had wooden handles.

§7.2.11. Finishing Tools (Figure 261)

Several different stones were tested as finishing tools. Some of these were also used as hammers (see §7.2.5 above). The coarser abrasives were granite and hard pumice. Medium-grade abrasives were limestone, marble, the fine-grained igneous hammer and soft pumice. Charcoal was used as a fine abrasive and haematite and agate for burnishing. Minoan whetstones and polishers in pumice, limestone and marble are extant (see §4.5.2). Granite and fine-grained igneous finishing tools have not been reported as far as I am aware. I am also unaware of any charcoal having been identified for use as a finishing tool, but such a use might be overlooked during excavation.

⁵⁶³ Evely, *Minoan Crafts* 1, 11, no. 142, fig. 5.142.

⁵⁶⁴ *Ibid.*, 86-96.

§7.3. The Reconstructions

§7.3.1. Annealing (Appendix Three, Part One)

A charcoal fire was lit in the hearth and encouraged to burn strongly by fanning. Using tongs, a copper billet was placed in the hearth and covered with burning charcoal. During one annealing session, strong winds blowing over the hearth annealed the billet within 10 minutes. Blowing through the blowpipe with the end 50 to 100 mm from the fuel annealed the copper in two to five minutes (**figure 262**). To anneal the entire billet, the end of the blowpipe was moved around so that the fuel all around the billet reached the required temperatures. The greatest temperature increases were limited to a circle approximately 100 mm in diameter directly under the blowpipe. Such localisation would be useful for annealing only selected parts of a large vessel if required. If, for example, the body of a vessel with a handle provision is formed and only the handle is to be worked, the handle could be annealed without annealing the body by careful placement of the vessel in the hearth and careful direction of the blowpipe.

While still glowing, the billet was removed from the hearth and quenched in the salt and vinegar solution to remove oxides. It was subsequently rinsed and excess oxide removed by rubbing it with fingers.

§7.3.2. Shaping Processes

In §3.1, I discussed whether the vessels would have been made directly from a thick, cast billet or whether the billet would have been initially forged into sheet and subsequently raised into the vessel form. The conclusion was that, for some small vessels, the billet might first be made into sheet. This was probably the case for the ladle in the Mitsotakis Collection discussed in §6.1.17. I concluded that large vessels would have been hammered directly from a billet by sinking and spiral-forging and additional shaping carried out with raising. Therefore, this was the method adopted for the reconstructions.

The specific hammering techniques were different for each form created. These are described in detail in Part Two of this volume. The general shaping processes, however, were similar for each piece. The initial stages required transforming the thick, flat disc-billet into a thin-walled, concave vessel. This form was subsequently adjusted into the final shape with localised sinking and raising.

Figure 263 illustrates the stages required to make the base section of the hydria. The diameter of the initial billet should ideally be similar to or larger than that of the final vessel-piece, since it is difficult to expand the rim diameter after shaping begins. It is not, however, impossible. The billet was first worked until it is a deep, thin-walled form. Next, the base was flattened with a combination of localised sinking from the inside around the desired outer-diameter of the base, and tapping down the base on air from the outside. In the third stage, the walls were raised to bring the rim in to the desired final diameter of the piece and to straighten the walls. In the last stage, forming the bulge at the base, the wall was raised in just above where the bulge was desired, and the bulge subsequently sunk further from the inside to increase its diameter. Stages such as these were required for all of the hydria pieces, each with slight variations for their final shaping.

On the four sections of the hydria, the initial shaping to a concave form was achieved with sinking (see Appendix Three, Part Two). The most effective way of carrying this out was by using a large pestle to sink the billet over a small hollow (**figure 264**). The cobblestone hammer was fairly ineffective for this, and the timber hammers were not tested because they do not have the weight and durability required for sinking thick material. Sinking was performed in spirals around the disc, alternating from rim to centre and centre to rim. Each hammer blow caused localised stretching and shaping which, when overlapped with surrounding hammer blows, resulted in the entire disc slowly thinning and becoming concave.

Each disc required dozens of rounds and annealing sessions to transform it into an appropriately-sized and shaped concave form which could be adapted into the final shape. Three of the hydria sections also had a hole cut in the base part-way through these processes so that the bottom-end could be shaped (**figure 265**; see §7.3.4 below on cutting).

Localised sinking was performed in a similar manner except that the spiral-form rounds were only carried out at the required points on the profile. The vessels were raised on the stake, when required (see Appendix Three, Part Three and **figure 266**). Several hammers were tested for their efficacy. The most effective was a large pestle or oblong: the type of stone did not matter. These were useful for raising thin (0.8 mm) and very thick (up to 3 mm) material. It proved too difficult to effect controlled hammer blows with the cobblestone due to its large faces. The oak hammer modelled on the Flag Fen hammer was not effective at all, since, with such an acute angle

between the handle and the head, it was very difficult to aim it accurately. The beech carver's mallet, however, was quite effective on thin material, although not as effective as the stone pestles.

The billet of the sterling silver one-handled basin was first thinned to approximately 2.5 mm by forging with a granite pestle on the limestone anvil (see Appendix Three, Part Four).

Initially, I had planned to transform this thinned billet into a thin, concave form with spiral-forging, but I quickly discovered that spiral-forging is hardly possible with a stone hammer and anvil. Instead, I continued the shaping with sinking, as for the hydria pieces. Further shaping included flattening the base slightly, caulking the rim and sinking the foot. Caulking was effected by forging the rim back into the wall with a pestle after almost every sinking round to keep it thick, and forging it heavily during the final shaping-stages to create a T-sectioned rim.

During the course of making the hydria sections, the effectiveness of a modern, hafted hammer was tested for sinking. During initial shaping, while the form is still relatively shallow, this hammer is functional, but once the form becomes deep, it is impossible to continue sinking because the handle of the hammer obstructs access to the deeper parts of the form, striking the rim. A handheld hammerstone does not have this problem, since the angle of the smith's arm can be adjusted to reach into any part of the concave form.

§7.3.3. Finishing Processes (Appendix Three, Part Five)

After the shaping processes, the walls of the vessels were fairly uneven, with dimples, ridges and furrows. The larger of these could be tapped out with gentle hammer blows from the inside or outside. The large walls of the hydria were smoothed by rubbing the walls from the inside with a piece of polished haematite against a wooden surface. This removed many of the smaller dimples in the walls. The walls of the silver one-handled basin were too small to carry out this process effectively.

The outer surfaces of the vessels had a fine, orange-peel texture and there were rough areas from hammer blows (**figure 267, a**). To create a polish, this was first cut back to a smooth surface. The granite, limestone, marble and pumice were all very effective for this. However, they left deep scratches which required further work with finer abrasives to make the surface smooth. The best tool was the fine-grained igneous stone, which cut very well but did not leave deep scratches (**figure 267, b**).

After the surface had been smoothed, the next stage was to cut it with a fine abrasive to remove the scratches from the previous abrasives, which left the surface dull. Slate and charcoal lubricated with water worked well for this, producing a reflective satin finish (figure 267, c). It is impossible to know what degree of polish Minoan vessels had after their manufacture, since the surfaces are now covered in corrosion. A reflective satin finish such as that produced with charcoal may have been the final finish. A high polish was produced in the reconstructions by burnishing the surfaces with the haematite and agate tools (figure 267, d). The problem with creating a polished surface on a functional metal object is that it tends to degrade over time as the object is used. To maintain the finish, it must be repolished. In addition, some metals, particularly copper, oxidise very quickly, making the surface dull and obscuring the polish. Tin and arsenic bronzes would not dull as quickly as copper due to the anti-oxidising qualities of these alloying components. It would certainly be more practical for Minoan vessels to be polished to a satin finish, since the wear of daily use is not so damaging to the finish.

§7.3.4. Further Working

Cutting (Appendix Three, Part Six)

Three sections of the hydria each had a hole cut in the base after most of the shaping was finished. The rim of the hole was then stretched out further to complete each section. The holes were cut with a chisel and hammer (figure 268). The metal sat on wood, which provides a surface with enough resistance to help the chisel cut through the metal, but not so hard that the chisel was quickly made blunt. Initial tests with a butt chisel showed that this type of chisel is unsuitable because it creates small tears in the material at the four corners of the rectangular cut. Such tears must be avoided because during later hammering they tear further into the vessel wall. A chisel with a curved cutting-face worked perfectly, and peripheral tears did not occur at all. The sterling silver chisel worked well but required resharpening approximately halfway around the circumference of the larger holes. All of the stone hammers were useable, but the basalt cobblestone was particularly suitable because of its large working faces.

The rim of the top section of the hydria had to be trimmed to straighten it after the shaping processes before the rim was folded over. This material was 3 mm thick. The sterling silver chisel created a channel in the material but was quickly made blunt and was not capable of cutting it, even with repeated annealing (figure 269). Bronze chisels

for such tasks must have had fairly high percentages of tin. The rim was folded over with a pestle.

Hole-Making (Appendix Three, Part Seven)

In §4.6.2, it was established that there were probably no materials in the Bronze Age capable of drilling metal, so holes must have been punched. A number of methods were tested with the silver punch. The simplest of these was to hammer the punch into the material. This creates a funnel-shaped hole with rupture prongs (**figure 270**, centre and **figure 271**, centre), which can be cut back with an abrasive stone (**figure 270**, right and **figure 271**, right). This method is effective on thin sheet but difficult on material over 1.5 mm thick because the silver punch quickly became blunt. Another method discovered is to punch the sheet enough to create a dimple on the reverse which is then cut down with an abrasive stone, leaving a small hole behind.

The method described by Rostoker was also tested (see §4.6.2).⁵⁶⁵ The punch was first driven into the sheet from one side deep enough to create a dimple on the reverse. The dimple was hammered flat and the punch driven through from the second side. This was repeated, alternating between sides until a small hole formed (**figure 270**, left and **figure 271**, left). Rostoker describes stretching the hole further with an awl, but I did not find it necessary. The method was effective on both thin and thick material (**figure 270**, left, **figure 271**, left and **figure 272**). On material over 3 mm thick, a harder material was required for the punch. A steel punch was used successfully on material 6 mm thick; some higher-percentage tin-bronzes might be equally effective. As for striking the chisel, all of the hammers worked, but the basalt cobble was particularly good because of its broad working surfaces.

Another method for hole-making was discovered during experimentation. On the seams of the hydria, after holes had been made on an outer section, holes needed to be made on the inner section which were perfectly aligned with these. The inner piece was punched through the hole of the outer section, pushing the material through the pre-formed hole on the outer section. After a few hammer blows, a hole was created by the shearing action of the punch forcing the material against the edges of the pre-formed hole underneath (**figure 273**).

⁵⁶⁵ Rostoker, "Ancient Techniques for Making Holes in Metal Sheet."

Riveting (Appendix Three, Part Eight)

Rivets were used to join the four sections of the hydria and to attach its two handles. The order in which this was carried out was carefully considered beforehand so that all of the joins would be accessible for hammering. The base section was first joined to the middle section and the top section to the shoulder section. The lower handle was then attached to the lower half and the upper handle to the upper half. Lastly, the two halves were joined at the middle seam. This seam was closed last because, with the rest of the vessel closed, the inside of this seam was the most accessible by reaching through the neck. The upper seam would have been at a difficult angle to hammer and the lower seam too far inside to reach comfortably.

After initial experimentation, I found that the best way to make the rivets is to cut each rivet length from a rod and make the first head before threading it through the vessel pieces. Round rod was used and the lengths were cut with a jeweller's saw. Since Minoan smiths could only cut metal with a chisel, which deforms the material as it cuts, each rivet would have to be forged back into shape after cutting, since it would not fit through the holes in the vessel otherwise. If square rod were used, it would be much easier to forge it back into shape after cutting than round rod.

Usually, the first step in making a rivet is to forge one head before threading the rivet through the holes, because it is difficult to work on both heads after it is in place. One method, which is only possible with large rivets such as those in the seams and handles of the hydria, is to stand the rivet upright and forge the upper end to flare it out. A disadvantage with this method is that the lower end is usually deformed and thickened as well, making it too large to fit through the holes. It is also cumbersome, because the rivet is impossible to hold in place while forging.

After experimentation, I found that a simple jig made from a brass plate with a hole slightly larger than the rivet shaft helped to hold the rivet for forging. It also helped with forming the head. The jig was placed on a hardwood surface and the rivet placed in the hole (**figure 274, a**). The jig only allows one third of the rivet-shaft to protrude from the top of the hole, and this is forged down against the brass plate to create the head (**figure 274, b, c** and **figure 275**). The hardwood surface underneath was hard enough to provide resistance to forge against but soft enough for the end of the rivet to dig into it somewhat during forging. This prevented deformation of the bottom end of the rivet.

The jig was made from brass because the material must be harder than the rivet so that it does not deform during forging. A Minoan equivalent could have been bronze or even stone. Another method tested was to drill a hole in hardwood deep enough so that one third of the rivet protruded above and to forge the head in the same way. This method worked reasonably well, although the rivets frequently stuck in the hole.

The second stage is putting the rivet through the holes and closing the second end. The first end needs to sit on a solid surface which provides the resistance necessary to forge the second end closed. Wood was inadequate because the first head tends to dig into it, preventing proper closure of the rivet, so the supporting surface had to be stone. On parts of the vessel which are accessible with a hammer from the inside, the vessel was laid across the limestone anvil so that the first rivet-head rested on the anvil's surface with the vessel carefully balanced so that its walls did not touch the anvil (**figure 276**). This was easier with the help of an assistant to hold the vessel in place. The second head could then be forged down from the inside. As well as closing the second head, this caused the first head to spread further, sealing the hole in the vessel wall (**figure 277**). When joining the base section to the middle section and the top section to the shoulder section, the inside of the vessel was easily accessible. The third seam which joined these two halves together was more difficult because the vessel was now closed, and the only point of access was through the neck. This meant that it was not possible to see the rivet-heads while forging them, so it was done by touch and by feeling and listening to the difference of vibrations when the rivet-head was correctly struck.

Sometimes it was impossible to hammer from the inside of the vessel to close the second head. This was the case when the upper handle was being attached to the neck of the hydria. In order to support the first rivet-head on stone, the neck was held over the stake and a stone of the appropriate shape, in this case the small-grained igneous hammer, was inserted between the stake and the vessel wall (**figure 278**). This provided the support necessary to close the second rivet-head.

The pestles and the cobblestone were both suitable for forging the rivet heads. Throughout most of the process of attaching the rivets, I used a granite pestle or the igneous oblong stone. When the last row of rivets was being fixed in place, to close the heads on the inside, where it was not possible to see the rivets to forge them, I found that the cobblestone was ideal, because its large working faces decreased the chances of accidentally missing the rivet head.

Repair

During shaping of the middle section of the hydria, a thin part of the wall developed some small tears. This probably occurred because copper is particularly fragile when it is thin; this is less likely to occur with bronze. Work could not continue because any further hammering would have opened the tears further. A Minoan smith encountering this problem would have had to start the section again. Rather than doing this, I temporarily closed the tears with silver solder; an option which Minoan smiths did not have (see §4.6.2). This is not a permanent solution because solder cannot hold tears closed under further stretching. The solder lasted for the duration of the rest of the shaping, but the tears did begin to open further.

This presented an opportunity to make a repair patch such as those found on some Minoan vessels (see §1.2.2 and §6.1.8). A small piece of copper was forged into thin sheet, holes were made around the patch and in the vessel wall around the damage, and the two were riveted together (**figure 279**).

§7.4. Discussion of the Results

§7.4.1. The Processes and Equipment

The results show that pi-hearths are entirely suitable for annealing vessels. This is not surprising, since the temperatures required are so low. The use of a blowpipe for draft also proved successful, as did a strong wind. The blowpipe is particularly useful because it allows for localised annealing which is beneficial when a small part of the vessel needs to be annealed rather than the whole.

All of the tested hammers were useful at various stages of the process except the replica of the Flag Fen hammer. Pestles and oblong stones are more suitable for sinking than any of the other hammers, and can also be used to raise thick and thin material, caulk rims, strike chisels and punches, and forge rivet-heads. The cobblestone is less useful for precise work required for the shaping stages, but works well for general forging such as closing rivet-heads and for striking chisels and punches. A wooden carver's mallet is suitable for raising thin sheet. It is certainly clear that it is not necessary to use metal hammers to make Minoan vessels. Hafted hammers have limited usefulness during the sinking stages because once the vessel becomes deep, the handle inhibits the hammer-head from reaching into deeper parts. Hammers with handles may

have been used during raising stages, but the reconstructions show that they were not necessary.

It does not seem to matter what type of stone is used for hammering, as long as it is not a fragile stone such as slate or pumice. Igneous stones are particularly useful because they are hard-wearing and long-lasting. The oblong, fine-grained igneous stone was one of the most useful of the replicated hammers. It was suitable for almost all of the hammering tasks and even as a small anvil during some of the riveting stages, and was the best abrasive for coarse cutting during the finishing stages.

It is clear that Minoan vessels did not require the use of a metal stake. Straight, wooden stakes are suitable. A limestone anvil is ideal for forging, though not for spiral-forging.

In the absence of planishing to smooth out vessel walls, an alternative method had to be sought which made use of the available tools and materials. The technique which I found worked well was first to gently tap out the larger irregularities and secondly to press out smaller dimples by rubbing the entire wall against a timber surface with a smooth, polished stone. It is impossible to determine if such a technique was used by Minoan smiths, because such processes leave no evidence.

The various abrasive tools tested were all suitable for coarse cutting of the surface, which is unsurprising since similar materials are used today. That the small-grained igneous oblong hammerstone was particularly suitable is a useful discovery. The use of charcoal as an abrasive is not attested, though I am not aware whether excavators have considered the possibility. The matter of the degree of polish on Minoan vessels is unresolvable, but the experimentation here shows that it was certainly possible to achieve a high polish by burnishing the surface with some of the stone types which were used to make sealstones such as haematite and agate.

Chisels with curved cutting-faces are ideal for neatly cutting sheet. The sterling silver chisel, the hardness of which is close to that of some lower-tin bronzes, was adequate for cutting thin sheet, but inadequate for cutting thicker material. Chisels of high-tin bronze must have been used.

Experimentation with punches for hole-making revealed that there are numerous methods, and it would be very difficult to determine which of these methods might have been used. It is more than likely that the technique varied from smith to smith. At the very least, just hammering the sharp end of a punch into the metal works perfectly well.

Tests of riveting methods showed that a stone anvil is essential for creating flush-head rivets. The manner in which the first rivet-head is made varies. The use of a jig in experimentation was the most efficient given the resources available, but different smiths may have used different techniques. The second head was made by supporting the first on the stone anvil, and wood was found to be unsuitable because the first head would dig into it during forging. For mushroom-head rivets, which were not tested in the reconstructions, if the bulbous end were rested on stone, it would probably be damaged. Such rivet-heads could probably be rested on wood, however, because the larger surface area and smooth profile of the head would probably reduce its tendency to dig into the wood.

A fair amount of forethought is required for piecing together a complicated vessel such as a hydria. The order in which the pieces are connected and whether rivets are forged from the inside or outside must be planned according to how accessible parts of the vessel are to the hammer and anvil.

§7.4.2. The Physical Experience of Using Minoan Metalsmithing Equipment

A significant result of using this equipment was the physical trauma caused by using unhafted hammers. Some degree of injury is usual in metalsmithing. Typical injuries include superficial damage such as blisters on the hammering hand, cuts and blisters on the other hand from the vessel's rim rubbing the hand during hammering, and muscle fatigue from the repetitive hammering action, resulting in muscle inflammation and stiffness. When such injuries occurred during the reconstructions, they were not unexpected. Some more serious injuries resulted from using a hammer without a handle. A handle on a hammer reduces the amount of effort required by the user, but without a handle, all of the force applied to the metal is applied directly by the user. This means that the muscles and tendons are worked significantly harder. Additionally, a handle reduces the force of the shockwaves from the hammer blows which are transferred into the hand and arm. Without a handle, shock waves transfer directly into the hand, arm and shoulder, bruising hand joints and tendons and jarring muscles in the hand, arm, shoulder, neck and back. The damage is exacerbated when sinking deep inside a concave form, because the arm has to be twisted into uncomfortable angles.

During the months of hammering the vessels, pain in the wrists of both arms was often debilitating, indicating the development of tendinitis. The fingers of the hammering hand were frequently numb, possibly indicating the development of carpal

tunnel syndrome. The joints of the fingers on the hammering hand were bruised and swollen, especially after raising and forging. On many occasions, the middle joints of the middle and fourth fingers (the *proximal interphalangeal joints*) on the hammering hand were so swollen that they became immobile. Even though protective measures were taken – shock-absorbing mitts, support bands around the wrists and upper forearms, wrist splints during periods of rest – the physical damage was significant. The various injuries caused the need for constant breaks on days when hammering was carried out and for longer breaks after a day of hammering. As a rule of thumb, six hours of hammering, including regular breaks of 15 to 30 minutes, required at least 24 hours of recovery before hammering could continue. This was not just required to avoid pain and further injury but because it was not possible to continue working, since the effectiveness of the hammering was severely reduced.

All of these injuries present the danger of longer-term damage which could lead to longer periods of rest being required, from several weeks to months. The type of damage sustained could even lead to permanent disability over the long term. Repetitive strain injury and tendinitis can require months of recovery and carpal tunnel syndrome can be permanently debilitating. Premature osteoarthritis resulting from wearing of the joints is also highly likely.

The finishing processes, by contrast, are gentle. The smith must sit rubbing abrasives on the vessel surface for hours or days. This is an activity which lends itself to social interaction in much the same way as knitting or embroidery do today. An individual may work amongst others and chat or even share the work. Because finishing the hydria was such a time-consuming task, I asked two other metalsmiths to help me. We sat, the three of us around the hydria, each working on a different side, and talked. It is easy to visualise a similar situation in a Minoan workshop or even a home. Finishing is also a task which does not require much skill. It is possible that children were assigned such work.

§7.4.3. Time

Hammering the hydria sections took approximately four months of working for six hours every second day (including weekends), with frequent breaks. Attaching the handles and joining the pieces took approximately three full days and finishing took two full days with the assistance of two others. The one-handed basin took approximately ten days in total. Unfortunately, this does not help to determine how long it would have

taken a Minoan smith to accomplish the same.⁵⁶⁶ Because I was learning how to use the equipment while making the vessels, I made several mistakes which took time to fix. It is possible that future reconstructions might yield more useful information about time-spans now that the methods are understood. However, there are also so many unknown variables. We do not know whether a vessel such as a hydria was made by one worker or several and what kind of division of labour there may have been. Was each vessel made and completed separately, or were they made in a production-line system? An individual working on such a vessel might take months, but if one person makes the billets, one the rivets, several do the hammering and others the finishing, perhaps it would be only a matter of weeks.

§7.4.4. Quality and Experience

The vessels made for this study are by no means of the standard of quality of the equivalent Minoan vessels. This is largely a result of my inexperience with some of the tools and methods. The walls of Minoan vessels are less dimpled, showing skilled use of finishing tools. Since I have now made this small group of vessels and since I have gained experience with these methods and tools, vessels made at a later stage would be significantly better. My lack of experience in using rivets for vessel construction caused several problems. I was not able to achieve a seal at the joins on the hydria, although it is possible that Minoan hydrias were not watertight but were sealed with a substance such as wax. Some of the rivets I made at earlier stages were not closed well, but as riveting progressed their quality improved. Many of the rivet-heads cut into the vessel-wall when they were forged closed, creating leaks. This is partly because I was still exploring the technique, but more significantly, the copper walls were very soft and easily damaged. If bronze or another harder metal had been used, this should not have been a problem. Such problems indicate that vessel-making was a complex craft practised by skilled and experienced artisans.

⁵⁶⁶ Jeffrey, "Experiential and Experimental Archaeology," 15.

Conclusions

The primary aim of this study has been to reconstruct the way in which metal vessels were made in Crete during the Bronze Age. Secondary to this aim was to provide a thorough and detailed technical description of this process which is understandable to scholars without metalworking experience. This would clarify the manner in which hammered metal vessels are made and provide reference material for future scholarship. The first part of this chapter brings together all of the findings from this study: previous theories about Bronze Age vessel construction, information from archaeological materials and metallurgical sites and, lastly, replication of equipment and techniques. The result is a reconstruction of the entire process from beginning to end.

In the course of the study, we have also made a number of interesting insights into the working practices of Minoan metalsmiths, the interpretation of Minoan metallurgical equipment and sites, and how Minoan vessels fit into the broader context of metal-vessel manufacture during the Bronze Age. These are discussed in the second section of this chapter. In the third section, the contribution and significance of this study is discussed, and in the last section, I recommend some avenues for further research arising from this study.

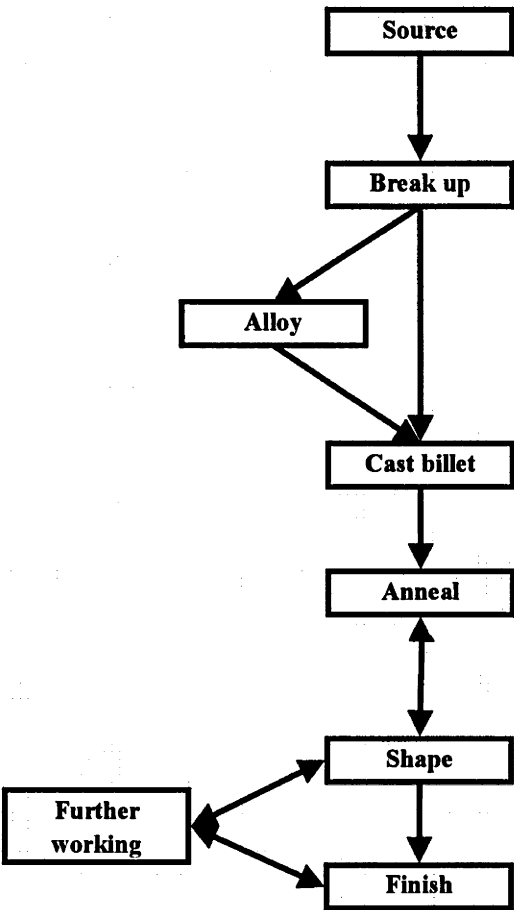
§8.1. Reconstruction of the Minoan Vessel-Making Process

The process for making hammered vessels in Minoan Crete which has been reconstructed in this study is as follows:

1. sourcing the metal
2. creating the blank from which a vessel can be made by:
 - breaking up the ingot or scrap
 - alloying
 - casting a billet
3. annealing
4. shaping
5. finishing
6. further working

The tasks within the process are not necessarily carried out in a linear fashion. Annealing, of course, is repeated throughout the shaping stages, and some of the techniques listed under further working may sometimes be performed during shaping or before finishing. In order to illustrate these variations and interactions, the tasks within the process are better illustrated in a flow-chart (Chart 4).

Chart 4. Basic Tasks within the Minoan Vessel-Making Process



§8.1.1. Sourcing the Metal

There is strong evidence to suggest that mining and smelting of metals was not carried out in Crete during the periods when metal vessels were being made. Rather, metal was imported from abroad and distribution appears to have been controlled usually by the palaces. Copper must have been allocated to a workshop in the form of whole or part oxide or bun ingots. Tin might have come in metallic or mineral form.

Vessels may have been made from recycled scrap metal collected within the workshop or traded within the community. In such cases, careful selection of the alloys

would have been necessary. Some types of vessel, particularly those which require extensive hammering, would have been very difficult to make from alloys which had originally been mixed for tools such as chisels and axes, which require high-tin bronzes capable of holding a sharp edge. Different alloys may have been identified by colour or by testing the material's working properties to judge its suitability for the task at hand.

§8.1.2. Breaking up the Ingot or Scrap

An ingot could be broken into smaller pieces with a process described by Agricola. It is placed on an open hearth in such a way as to allow air to circulate around it, for example by supporting it on rocks, and then covered with charcoal. A draught is introduced with blowpipes, skin bellows or pot bellows. The metal is heated for several hours and removed with copper or bronze tongs, pieces of timber or hand-held rocks. At this point, with the ingot on the ground or perhaps on an anvil, it is struck repeatedly with heavy bronze or stone sledgehammers until it shatters. Some suitable bronze hammers are extant, but not common.

Scraps and other small pieces may have been cut into pieces with a chisel and hammer. Reconstructions carried out for this study indicate that chisels for such work must have been of quite high-percentage tin bronzes, since lower hardness ranges are not capable of separating thick material. Most hammers are suitable for striking chisels.

§8.1.3. Alloying

Alloying may not always have been carried out, especially for precious metals, but analyses of bronze vessels indicate that the few extant bronze vessels from the Protopalatial period were made from arsenic bronzes. From the Neopalatial period, tin bronzes are the norm for vessels, ranging between 1 and 17.5% tin, although the preferred range seems to be 1 to 12%. Analyses of oxhide ingots extant from Crete show that they are unalloyed copper. This indicates that metalworkers probably mixed alloys after the materials had been distributed rather than receiving pre-mixed bronzes.

The alloying components may have been measured out with balance scales, which are relatively common throughout the Aegean. Alternatively, the required components may have been estimated. These could have been mixed together in the crucible before heating, or the base metal melted first and the alloying component(s) sprinkled over. At this stage the molten metal may require stirring. A green stick used for this purpose

helps to remove any oxides which have formed. From this point the usual casting procedure, described in the following section, can be carried out.

§8.1.4. Casting the Billet

In Chapter Four, we established that most Minoan vessels would have been hammered out directly from a disc-billet, although some smaller vessels may have been made from sheet which had been hammered out from such a billet. There is some suggestion that a small number of vessels were cast and that others were cast as a proto-vessel and subsequently hammered into shape. In the absence of metallographic analyses, it is difficult to say whether or not this was the case. There is little evidence that Minoan casting technology was capable of producing vessels in such a way. A billet for making a vessel was probably either a simple disc or a disc with a provision on the edge for a handle or spout. Provisions for handles were sometimes cast complete in the final form, but were often a tab or rod which would be forged into shape.

Bivalve stone moulds made from schist, limestone, steatite, chlorite or sandstone would have been used to cast disc-billets, as two extant moulds from Malia indicate. One broad-rimmed basin which I examined was clearly hammered from a billet cast by lost-wax, suggesting that this method was often used. Lost-wax casting is more versatile for casting billets, because different billet sizes and shapes can be produced. Only one size of billet can be made from a stone mould

Having selected the metal and perhaps alloying elements, the smith places them into a clay or stone crucible. Flux may also be added to the crucible. Possible fluxes include bone ash, haematite, oils, fats, honey, resins, dung, beeswax, soda, natron, borax, salt or charcoal. A stone mould would be prepared by coating the interior surface with carbon in the form of either soot or oil to aid removal of the cast item later, and the two halves bound together with copper wire.

The type of hearth which may have been used to melt the metal is still unknown. Pi-shaped hearths are a possibility, but have not been tested, and none extant show any evidence of casting. Crucible hearths are another possibility. The heating patterns on some extant crucibles indicate that they may have been used as hearths. Fuel may have been one of a number of substances. Some materials which have been proposed include wood, charcoal, olive pressings, chaff, reeds, straw and bones. Charcoal made from olive wood was probably commonly used.

The empty mould is placed in the hearth and heated gently to reduce thermal shock during the cast. The crucible is placed on top of or under the fuel in the hearth and an artificial draught introduced via blow pipes, skin bellows or pot bellows. When the metal is satisfactorily liquefied, it is stirred with a stick to ensure no solid lumps remain and that the mixing of the alloying components has been achieved, and to help remove slags and oxides. The crucible is quickly removed from the heat with metal or wooden tongs, continuing to be stirred or swirled to keep the temperature even. The molten metal is poured immediately into the hot mould. The mould is opened, or broken in the case of the lost-wax process. The cast billet may then be quenched in water held in any vessel large enough to take it, probably one of ceramic, but also possibly of stone or metal.

§8.1.5. Annealing

Being hard from the cast or from hammering, the billet needs to be annealed to soften the material for further working. The metal is buried in the hearth and a draught introduced. The reconstructions showed that a pi-hearth with charcoal fuel and a blow-pipe are suitable for annealing. The progress of the annealing metal can be observed through the charcoal. When it is consistently annealed, it is removed from the hearth and quenched. If a pickling liquid is used to remove oxides on the surface, it may be quenched in this. What pickling substance might have been used is unknown, but some possible ingredients include vinegar, brine, urine and bird dung. Otherwise, oxide may have been removed with abrasives such as those used during finishing processes.

§8.1.6. Shaping

Equipment

Since it is likely that only small Minoan vessels were hammered from sheet, the associated use of crimping to establish a concave form to then raise is unlikely. Those forms which may have been made from pre-hammered sheet, like scoops and some cups and bowls, are too small anyway to require crimping. Sinking achieves the same ends, is less complicated and, unlike crimping, can be used to make small vessels.

There are few bronze hammers extant from Crete, and even fewer which are suitable for vessel-making. The reconstructions showed that they were unnecessary, since stone hammers, especially oblong and pestle shapes, work very well for all of the different

hammering processes. Cobblestones are suitable for simple tasks such as forging and striking tools. Wooden hammers are also suitable, but only for raising. Simple wooden mallets such as those used by metalsmiths today are likely, and New Kingdom Egyptian carver's mallets were shown to be suitable in reconstructions. It is also possible that bone and horn hammers were used, but no examples of such tools have yet been noted. The reconstructions indicate that not only were hafted hammers not necessary for making Minoan vessels, but they may in fact have inhibited some of the shaping processes. This is especially the case with sinking, which seems to have been the main shaping process used. Hafted hammers could have been used for raising, and wooden hammers for raising must have had handles, but unhafted stone hammers are perfectly suitable, though their use for prolonged periods could cause the smith permanent physical damage. The suitability of unhafted hammers for making Minoan vessel forms suggests that they were commonly used. Certainly, the dearth of hafted hammers, even though other tools such as axes were hafted, supports the conclusion that they were uncommon.

The type of stone used for hammering does not seem to be as critical as the shape, although very fragile stones such as slate or pumice are, of course, unsuitable. This suggests that specific types of stone were not necessarily sought out since most are suitable. The various stones from which extant hammering tools were made—limestone, marble, sandstone and igneous stones – are all suitable for hammering vessels. More fragile types such as marble tend to deteriorate faster than others, while fine-grained igneous stones are very hard-wearing. These findings suggest that when searching for hammering tools, smiths would have been more concerned about the shape than the type of stone. Certainly, fine-grained igneous stones such as andesite, which is a common hammer-stone type, must have been favoured for their versatility.

Some limestone slabs found in the vicinity of metallurgical remains have been proposed as anvils. The replicated limestone anvil used in the present reconstructions was very suitable for forging. That bronze anvils were used is a possibility, but they were probably uncommon. The same extant limestone slabs, some of which have hollows ground into them, may also have been used for sinking, though these hollows are large and shallow, making them suitable only for large-scale sinking rather than localised stretching of billets. Hollows carved into wood are more likely.

The archaeological evidence suggests that bronze stakes were very rare, and the reconstructions carried out showed that they were unnecessary. Although their presence

in Crete can only be postulated, hollows and stakes made from wood are perfectly suited to making Minoan vessel forms. With an absence of extant tools, it is difficult to imagine that they could have been made from anything else.

Since there is no surviving evidence, it is difficult to say how a stake was secured for hammering over. Evidence from Egyptian metalsmithing depictions present some possibilities. The stake may have been attached to a post or leaned against a support and its non-working-end weighed down for stability.

Process

Depending on the dimensions of the cast billet and the vessel being made, slightly different hammering approaches may be taken at this stage. For small vessels such as ladles, the billet would first be hammered into sheet. A thick billet for a larger vessel might be forged enough to thin the material and expand the diameter before shaping begins. In the reconstructions, I found that, ideally, the diameter should be at least as large as if not larger than the final diameter of the vessel's rim, because the sinking process tends to reduce the diameter of the rim, and it is tedious to increase it afterwards.

Shaping begins by sinking the billet into a thin-walled, concave shape. The billet must be annealed and sinking repeated many times until the walls are the required height. Minoan vessels have walls as thin as 0.5 mm in some places, and are rarely more than 1 mm thick. This would have been a result of the early shaping-stages. At this point, further shaping to achieve the final form may be carried out with localised sinking, raising or a combination of the two, depending on the final form.

Where a spout or handle extending from the material of the body is required, this is now forged into shape by sinking, forging or a combination of the two. A dropped foot may be made by sinking.

Most vessels would have their rims formed at this point, before finishing begins. The vessels themselves show that most rims were caulked to some extent, even when their rims were strengthened by other means such as folding or rolling. Heavily caulked rims such as those on one-handled basins would have been caulked throughout most of the forming stages to achieve their broad rim.

§8.1.7. Finishing Processes

Minoan vessels were probably not planished; the dearth of metal tools suggests this, and the vessels themselves show none of the characteristic marks on their inner or outer surfaces. Unfortunately, the method used to smooth out wall irregularities cannot be ascertained by observing the vessels. It is likely that larger irregularities were lightly tapped into shape. Reconstructions showed that rubbing the walls on a wooden surface works well if used in addition to light tapping. It is unknown whether either of these techniques was used, but they are successful methods for smoothing the walls with the equipment available.

A coarse-grade abrasive is rubbed over the entire surface to cut the fabric down to an even surface. Extant tools used as abrasives include pumice, limestone, emery, siltstone, slate, sandstone, fine-grained igneous stones and quartzite. The tests carried out with slate, limestone, marble, pumice and igneous stones were all successful for coarse cutting, indicating that most stone types are suitable. Some are better than others, and fine-grained igneous stones are particularly good. The best fine abrasive tested to create a satin polish was charcoal. Materials which have been proposed by others as fine abrasives include clay, limestone, marble and pumice, but I found that these were quite coarse and not suitable for a polished finish. It is not clear from extant vessels how highly polished they were. Burnishing the reconstructed vessels with agate and haematite, which are stones from which Minoan seals were sometimes made, proved successful for producing a high polish. Other stones used for seal-making, such as quartzes, when polished, would also be suitable. Whether or not they were used to polish metal is unknown.

§8.1.8. Further Working

The few vessels which remain from before the Neopalatial period have handles and legs which were forged from billets, suggesting that this method was common on early vessels. From the Neopalatial period on, the practice continued, but handles, as well as legs, rims and masking bands, were more commonly cast by the lost-wax process. The alloys for these cast appendages range from low to high tin content and frequently contain lead, which would have improved the alloy's casting properties. On close inspection it was found that on some vessels, handles were cast with rivet shafts as part of the attachment plate, and, on others, the hole for the connecting rivet to pass through was incorporated into the original wax.

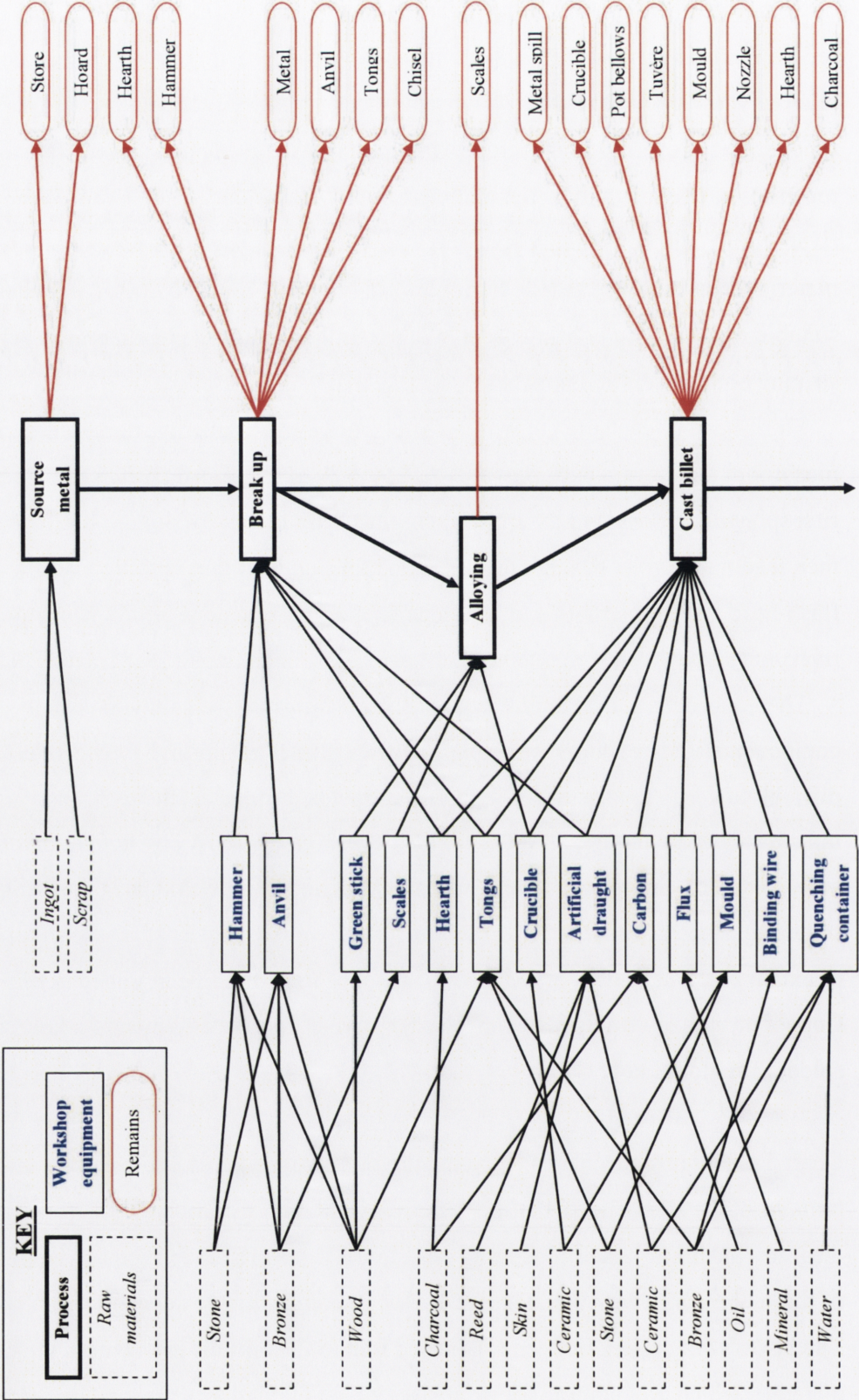
Some vessels required cutting at various stages of their manufacture. The reconstructions show that thin sheet metal could be cut with curved chisels made from relatively low-tin bronzes, but, for cutting thicker material, chisels must have had higher tin contents. Several Minoan chisels have appropriately-shaped cutting-faces. Since materials hard enough to drill metal were not available during the Bronze Age, holes for rivets could only be made by punching. Like chisels, punches used to pierce thick material must have been made from high-tin bronzes. Low-tin bronze punches were suitable for punching holes in sheet. All extant Minoan stone hammers are suitable for striking both chisels and punches.

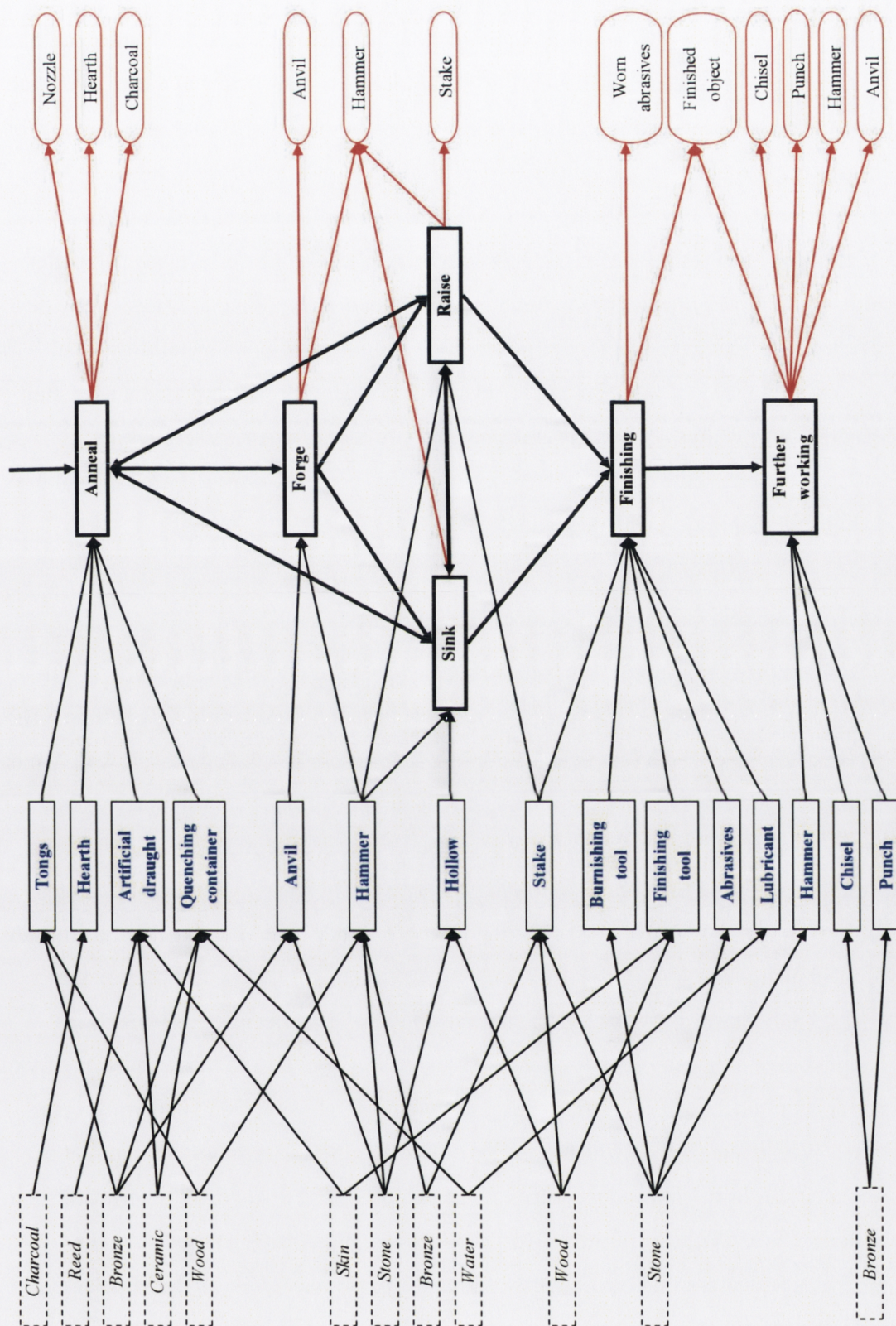
Flush-head rivets were cut with a chisel from a rod, probably square in section, and mushroom rivets were cast, probably by lost wax. Flush-head rivets were attached by first splaying out one end by forging, possibly with the use of a jig to hold the rivet still, then feeding the rivet through the holes and forging the other end flat over the hole. For flush-head rivets, the first head had to be supported on a stone anvil. Mushroom-head rivets may have been supported on timber to prevent damage to the larger head.

There has been some suggestion that some Minoan vessels may have had components soldered together. None of the examples proposed have been tested, so it is difficult to verify the use of soldering on copper or bronze. If the technique was used, it must have been uncommon, since so few extant vessels show any indication of having been soldered. On precious-metal vessels, Minoan smiths could have used colloid hard-soldering, since this method was used on gold jewellery, but none of the small number of extant precious metal vessels from Crete appears to have been joined in this manner. Copper or bronze vessels may conceivably have been joined with hard solder, but soft solders are more likely.

Chart 5 elaborates on Chart 4, showing the resources required for each task and what remains of these might exist in the archaeological record. Down the vertical line of the diagram, the black boxes containing bold font list the processes themselves. To the left of these, the boxes with blue text list the workshop resources needed for each process. The boxes with broken lines and italicised font to the farthest left contain the raw materials which are required for each piece of equipment or process. The red oval boxes to the farthest right indicate potential archaeological remains. This flow-chart can be used to identify how equipment and seeming debris found at a site might be interpreted in relation to vessel-making.

Chart 5. The Minoan Hammered-Vessel Manufacturing Process





§8.2. The Implications of this Study

The results of this study have some implications for broader studies of Minoan culture. Having replicated some of the metallurgical processes, we are now in a better position to understand the working practices of Minoan metalsmiths. This has implications for how we are to interpret the role of a metal workshop within a broader social system. Furthermore, we may be able to gain some insight into the internal structure of a workshop. As a result of clarifying some metallurgical processes, we are also better able to interpret evidence which might suggest the location of metallurgical activities. Primarily, it should be clear by now that there is more to Minoan metallurgy than casting, and we should be looking for evidence besides that which pertains to casting. Finally, through this study it has become apparent that Minoan vessel-making techniques were quite different from those of other contemporary Bronze Age cultures, leading us to question why this is the case.

§8.2.1. Working Practices of Minoan Metalsmiths

The reconstructive aspect of this study revealed some of the physical aspects of this work which would affect the working practices of individuals within a workshop. The physical damage which I experienced during the process of making vessels with Minoan equipment indicates that a person who uses unhafted hammers continuously would probably become crippled within a few years. Some vessel types, especially hydrias, would probably require years of training and practice to master. If smiths became crippled within a few years of beginning their craft, they could not develop this mastery of the techniques.

This indicates that Minoan metalsmiths would not have been hammering continuously. This applies not only to vessel-making, but also to the production of tools which required extensive forging. Hammering must only have been undertaken part-time. Within a workshop which operates only part-time and with a small number of workers, smiths might produce wares for some of the year to augment other work such as agriculture. Within a full-time workshop, labour might be organised so that no individual is hammering continuously. Several smiths may work on the same vessel, reducing the amount of hammering carried out by each individual, or tasks may be rotated, so that an individual may change from hammering to finishing, wax-making, casting or hole-making. They might also undertake other tasks in the workshop such as tool-sharpening, jewellery-making and so on. Laffineur proposes that Mycenaean

artisans worked in multimedia workshops, and might also have worked in stone carving and faience.⁵⁶⁷ Such work practices would allow individuals to reduce their risk of permanent physical damage.

It is also worth examining the internal structure of workshops. It is unlikely that vessels were made by smiths who worked alone. The physical damage described above is one limiting factor. Additionally, during the reconstructions, I found that there were several times when an assistant was required. One example is during riveting, when having someone hold vessel pieces in place while I was occupied with striking rivets was essential. The assistance of others also reduces the amount of time required to finish a vessel, as was exemplified when other metalsmiths helped me to finish the hydria's surface.

The presence of assistants within a workshop raises the issues of family involvement, workshop hierarchy and apprenticeship. We might imagine a situation in which young people learn a craft by working alongside masters at a young age. Initially, they could help with tasks which require little skill: for example, holding items which are being worked on, or tedious and monotonous work such as finishing and polishing, hole-punching, cutting and rivet-making. Assistants could learn specialised skills by undertaking simple projects. Minoan vessels which are suitable include bowls and simple cups. More advanced projects would build on these skills. Tripod cauldrons, pans with hollow, vertical handles, one-handled basins, spouted vessels and lekanai, are intermediate projects which teach casting, basic shaping, raising to varying degrees of complexity, careful caulking and forging, and riveting. Hydrias, being the most complex vessel-type, require mastery of most these skills to a high degree of accuracy. Since they comprise such a large amount of material, which was also valuable, they must have been made by master smiths or by skilled apprentices who were carefully supervised.

As has been the case in recent centuries, those learning the craft may have been the children or other young relatives of masters, which ensures the future survival of the family. One might imagine such a scenario for the houses at Kommos, where double axes were apparently being produced in small-scale household industries. The same may also be the case for the workshops at the Artisans' Quarter at Mochlos which Brogan proposes were both the homes and working places of artisan families.⁵⁶⁸ The system of apprenticeship of children seems suitable for Minoan metalworking, given the

⁵⁶⁷ Laffineur, "Craftsmen and Craftsmanship," 198-199.

⁵⁶⁸ Brogan, "Metalworking at Mochlos," 161.

years of training required to produce the finest items for elite consumption. However, this may not necessarily have been limited to kin. The suggestion made by many that Mycenaean artisans learned Minoan vessel-making techniques under the tutelage of Minoan artisans would be explained by such workshop structures.

§8.2.2. Evidence for Vessel-Making at Minoan Sites

Only two Minoan sites which have been linked with metallurgy show strong evidence for vessel-making, and this evidence is indirect. Remains of lost-wax moulds for vessel handles from the Artisans' Quarter at LM IB Mochlos and LM IIIA2 or B Palaikastro suggest that vessels were probably made in these locations, since handles would have been made for specific vessels which had already been made. Weaker evidence for vessel manufacture comes from House C2 at LM IA Mochlos, where a pair of bronze discs was found, from MM III Malia, where two moulds for discs were found in the north-west quarter of the palace, and from the South Workshop at Quartier Mu, where possible vessel attachments have been recovered.

It is difficult to identify at which sites vessel-making took place because the same evidence can indicate the production of most other Minoan metal items. All items required casting at some point, if only to produce billets from ingots or scrap, and the production of most tools required forging and finishing, so casting and hammering remains do not necessarily indicate vessel manufacture. The only piece of equipment which is exclusive to vessel-manufacture is the stake, but other than the small number of bronze tools which may have been used as stakes, these do not survive.

Unfortunately, this means that vessel making might have occurred at all or none of the metallurgical sites discussed in Chapter Six.

This study has demonstrated that Minoan metallurgical activities were far from being limited to casting processes. Metallurgical sites are always identified by the presence of casting remains - moulds, crucibles, bellows, droplets and offcuts – but we have seen that casting plays only a small role in vessel-making. Hammering and annealing play significantly larger roles. The same is true of many Minoan metal objects. Many tools were forged from parts of cast billets, and even tools which were cast in shape, such as double-axes, would have been forged to improve their working qualities.⁵⁶⁹ If casting is

⁵⁶⁹ Metallographic analyses of Prepalatial copper tools from the Mesara Plain carried out by Tselios show that the tools which were made for utilitarian rather than votive reasons are invariably hammered after casting. Presumably, such practices were continued in later periods. T. Tselios, "Pre-Palatial Copper

removed from the equation, we are presented with the possibility that metalworking occurred at many more sites than are currently recognised; at any site, in fact, where hammering tools, finishing tools and a hearth, with or without casting evidence, are found.

Hammering may have been carried out at some distance from the location at which casting occurred. There are several reasons why this may have been the case. Casting requires a lot of space. Several people would need to be present for pumping bellows, lifting and pouring the molten metal and the various other, smaller tasks. Thus a large working-area is required in the vicinity of the hearth. In addition, it would be better to cast outside, where there is adequate natural light and ventilation. This might mean that the casting hearth was some distance from where the hammering, the bulk of the work, was carried out. Hearths producing such high temperatures must also have been kept well away from buildings to prevent wooden elements such as posts, beams and doors from catching fire. The reduction of pollution in the vicinity of living spaces may also have been a motivating factor. Another matter to consider is that casting may have been carried out in locations where the process could not be observed by outsiders.

Ethnographic examples of this practice exist, where a smith prevents others from observing the working procedure in order to obstruct outsiders from learning the craft, thus ensuring the high value of the products.⁵⁷⁰ One or more of these factors may help to explain why hearths used for casting are not often found.

A complicating factor for attempting to identify metallurgical sites which do not have evidence of casting is that many of the tools would have had other functions as well, both for crafts and domestic tasks. Hammers of various kinds were probably used for preparing dye and pigment materials for textiles and frescoes, for example, and must have played a role in food preparation; crushing grain is one example. Finishing tools may also have been kept by artisans of various crafts, woodworkers for example, to keep metal tools sharp. The same might be said for domestic tools. An analytical study of tool wear-marks which incorporates comparisons of tools used in experimental reconstructions may reveal characteristic marks. Images of the marks on the tools used for this study have not been included, because it is difficult to illustrate them in photographs.

Metalworking in the Mesara Plain, Crete," in *Aegean Metallurgy in the Bronze Age*, ed. Iris Tzachili (Athens: Ta Pragmata Publications, 2008).

⁵⁷⁰ e.g. J. Adair, *The Navajo and Pueblo Silversmiths* (Norman: University of Oklahoma Press, 1989), 125.

As well as keeping in mind the possibility that metalworking may have occurred at sites which do not show casting remains, scholars can contribute to metallurgical studies by examining other materials for evidence of use as tools. In this study, charcoal was found to be an invaluable fine abrasive. Inspection of individual pieces of charcoal for signs of faceting would be beneficial. Likewise, bones may show evidence of use as striking tools. Having illustrated in this study the methods and types of equipment used to make metal vessels, I hope that excavators will be able to use this information to identify more metallurgical sites and, in turn, discover more about Minoan metallurgy.

§8.2.3. Minoan Vessel-Making Equipment and Minoan Vessel Forms

Minoan vessels are unusual amongst the broader corpus of metal vessels made in contemporary Bronze Age societies because they are predominantly open forms. I posited in Chapter One that this might be because they were made predominantly by sinking and that only straight stakes were used for raising. Curved stakes for making closed vessels must be made from metal, but straight stakes can be made from wood. This observation seems to be supported by the near absence of metal stakes in Crete and the findings from the reconstructions that Minoan forms can be made on straight, wooden stakes. That sinking was the main process used to form the vessels was confirmed by reconstructions. Furthermore, the simple stone hammers which are common at Minoan sites are better suited to creating the vessel forms than hafted hammers, which are uncommon. It is reasonable to suggest that the reason why Minoan vessels are the shapes they are is because they were rarely made with metal stakes and hafted hammers.

It is difficult to say why Minoan smiths were creating open forms almost exclusively when their contemporaries elsewhere were creating closed forms. These other cultures must have been able to use metal stakes and perhaps also hafted hammers. This significant technological contrast between Crete and its neighbours could, but need not, be interpreted as ignorance of more advanced vessel-manufacturing technology. The fact that the riveted seams of some vessels were hidden beneath a decorative masking-band may reflect a desire to create one-piece closed vessels such as those of neighbouring peoples. However, that the Minoans had close trading relationships with neighbouring regions, particularly Egypt, suggests that complete ignorance of the techniques is unlikely. The evidence suggests that Minoan vessels were admired

abroad.⁵⁷¹ Minoan vessels in the Mycenaean Shaft Graves and their depictions in the Theban tombs might be cited as examples of this. Since the vessels were so successful, perhaps there was little incentive for smiths to alter their techniques.

The other important difference between Minoan vessels and those of their contemporaries is the significant size difference of many vessels. That the production of vessels from Egypt, Anatolia and further east was so dominated by raising suggests that they were usually made from pre-formed sheet, since it is not possible to raise metal which is more than a few millimetres thick. An advantage of hammering the vessel from a billet, as I have proposed that most Minoan vessels were made, is that it is a less laborious way to make large vessels. This may explain the presence of such large vessels in Crete and also on the mainland, which was so heavily influenced by Minoan craft, and the relative dearth of large vessels elsewhere. A comparative study of vessel-making equipment between Bronze Age cultures would provide some very interesting insights into these typological differences.

§8.3. The Contribution of this Study

The practical approach of this study has provided some original insights into Minoan metallurgy which have not previously been achieved. The perspective of a practising metalsmith allowed me to address some of the confusion and misconceptions in current scholarship about how metal might have been worked during the Bronze Age. I have also, I hope, explained the techniques used to make vessels in a manner which is accessible and useful for scholars working on similar material.

The application of replicated Minoan equipment in experimental reconstructions has not only helped us to understand how vessels were made, but has also provided new insights into the equipment used. We are now in a better position to understand the potential uses of some artefacts, which allows for new assessments of the activities carried out at some sites. We now know that Minoan vessels did not necessarily require the use of metal hammers, stakes and anvils, and also that even hafted hammers were not necessarily required. This is significant, because it indicates that there is not a missing class of tools. Rather, the few bronze tools and hafted hammers which are extant were probably unusual. This is not to say that they were never used, but that their near absence in Crete is not necessarily surprising. This discovery led to important

⁵⁷¹ Davis, *AGSW*, 332.

observations on the differences between Minoan vessel-making techniques and those of contemporary cultures.

The replication of Minoan metalsmithing processes has also allowed us to understand the practicalities of using this equipment and the social implications that the use of this technology has. The physical limitations of the human body play a significant role in the work practices of an artisan and this in turn affects the structure of the surrounding community. Findings such as these are very difficult to come by without experimental reconstruction.

The practical approach of this study was, however, entirely dependent on the work of others about the nature of metalworking in antiquity and of Minoan craft equipment and practices. By necessity, there is often a tendency for scholarship on ancient technology to isolate processes. This project has brought together many studies on individual metallurgical processes and placed them in a wider context, albeit still a small part of the whole picture of Minoan craft and technology.

§8.4. Avenues for Future Research

The practical approach of this study could be extended to understanding the vessel-making processes used in other cultures. In particular, it would be extremely informative in studies of the vessels of other prehistoric peoples, including Bronze Age Mesopotamian, Egyptian and Anatolian cultures and early Iron Age Greece and Cyprus. I would not, however, recommend the use of unhafted hammers for extensive replication because of the permanent damage it can cause to the practitioner.

In particular, this study could be extended to Mycenaean metal vessels. Although the tradition on the mainland appears to stem from that of Crete, there are some differences which may reflect influences from elsewhere. A wider-ranging study of vessel manufacture and metalsmithing equipment in the entire eastern Mediterranean and Near East might make it possible to trace the development of the craft and the path of its distribution throughout the region. In addition, it may reveal some important interactions between these peoples. The only study I am aware of which has attempted this is by Sherratt and Taylor, but their study focuses primarily on precious metal vessels and typological similarities.⁵⁷² The addition of the technological aspects and of copper alloy vessels would be extremely informative.

⁵⁷² Sherratt and Taylor, "Metal Vessels in Bronze Age Europe and the Context of Vulchetrun."

Further experimental reconstruction of other Minoan metallurgical processes would be very beneficial to the field. In particular, we might come to understand more about Minoan casting technology if experiments with casting were carried out with the types of hearths found in Crete, such as the pi-shaped hearths. Such experimentation might help to explain why it is that the hearths currently known apparently show no strong evidence of metallurgical use. In addition, further experimentation with Minoan tools might incorporate studying the ergonomics involved. In this study, I was not able to incorporate tests on the pros and cons of using tools from different positions, sitting versus standing, for example. Hammering while seated on the ground, which is probably how smiths operated during the Bronze Age, may reduce some of the damage caused to the user's body.

Metallographic analyses of Minoan vessels would greatly contribute to a better understanding of how some vessels were made. In particular, analyses of some of the vessels which are thought to have been cast complete or to have been cast as proto-vessels would help to clarify whether these techniques were used. Additionally, if analyses were able to confirm the theory that some vessels were cast complete with thin walls, it would mean that Minoan smiths were capable of far more sophisticated casting techniques than we are currently aware of. It would also be extremely informative if some suspected solder joins on bronze items were analysed in order to discover what the material is.

I would suggest that a number of matters raised in this study should be considered in the analysis of previously excavated material and in future excavations. It seems very likely that animal bones would have been used as hammers, if not for metallurgy, then at least for domestic purposes. Bones could be analysed for percussive damage, particularly large leg bones. Also, inspection of charcoal may show signs of its use as an abrasive.

During the assessment of the potential activities at a site, above all, it must be remembered that metalworking is not limited to casting. Excavators might therefore consider the presence of hammering and finishing tools in particular as potential evidence of metallurgical activities. Such tools may be used for other purposes, but it is hoped that, in some cases at least, context might help to support the assessment of these as metalworking tools. Studies involving comparative analyses of tool marks used for different activities in experimental reconstruction might help to pinpoint specific activities.

Part Two

The Workshop Report

The reconstructive experimentation carried out in the workshop for this study involved the manufacture of several vessels. Each vessel was made in order to address a specific set of aims. Thus, the production of each vessel tested certain processes and equipment which this study had indicated were used to create Minoan metal vessels. During initial experimentation, two small copper bowls were made in order to test some basic processes which would be used to create two larger Minoan vessel types (Experiments 1 and 2). The first of the Minoan types was a large copper hydria (Experiment 3) and the second a sterling silver one-handed basin (Experiment 5). In addition, some preliminary tests were carried out with copper to test methods for making the sterling silver one-handed basin as well as to test the effectiveness a pi-shaped hearth for annealing (Experiment 4).

Metals, Equipment and Tools

Materials

The metals used for the experiments were unalloyed copper and sterling silver. The reasons for using these are discussed in §7.2.1. The choice of material thickness was, to a large extent, determined by what materials were available to me. The archaeological evidence suggests that the minimum material thickness which would have been available to Minoan metalsmiths was probably no less than 3 mm and, in all probability, often thicker. For Experiments 1 and 2, the copper bowls, I used sheet 1.2 mm thick. Since these two bowls were largely to be quick preliminary experiments into tool techniques, the material thickness was not relevant. Ideally, for Experiment 3, the hydria, I would have preferred to make all four sections from material between 3 and 6 mm thick. However, when I began the hydria, the thickest copper sheet I could acquire was 2 mm thick, so the base section and middle section were made from this material. Although this did not seem ideal, I felt that this compromise would still provide useful results since 2 mm is too thick to be considered sheet, and thus would respond in a manner similar to that of thicker plate. Fortunately, by the time I came to making the shoulder and top sections, I was able to acquire 3 mm sheet, but no thicker.

The Heat Source

Most of the annealing of the vessels was accomplished with a natural gas torch because of time constraints and the complications associated with keeping a charcoal hearth burning for the months required to make the vessels. A pi-shaped hearth was built for a limited period of time in order to test its effectiveness for annealing (see §7.2.2 and figure 251).

The Blowpipe

I tried initially to find an organic material to use as a blowpipe but was unable to find any suitable material. Instead, I used a length of aluminium tube 620 mm long and with an internal diameter of 7 mm.

The Hammers

Basalt cobblestone (figure 252)	87x59x70 mm
Small marble pestle (figure 252)	length 121 mm large face convex, diam. 30 mm small face flat, diam. 21 mm
Large granite pestles (figure 252)	average length 170 average large face convex, diam. 44 mm average small face convex, diam. 25 mm
Small granite pestle (figure 252)	length 96 mm large face convex, diam. 29 mm small face convex, diam. 21 mm
Fine-grained igneous oblong (figure 252)	length 113, width 46, th. 24 mm both faces convex, 15x30 mm
Fine to medium-grained igneous oblong	length 145, max. width 67, max. th. 32 mm face 1 convex, 35x25 mm face 2 convex, 40x20 mm
Beech carver's mallet (figure 253)	head height 100, max diam. 98 mm handle length 132 mm

Oak-branch mallet (figure 254)	head length 165 mm
	face flat, diam. 30 mm
	handle length 260 mm

Wooden Hollows (Figures 255, 256 and 280)

For ease of reference, the hollows have abbreviated titles based on their relative diameter (L=large, M=medium or S=small), depth (S=shallow or D=deep) and material (E=hard eucalyptus or P=pine).

LSE	large-diameter, shallow, eucalyptus; diam. 185, depth 26 mm
SDP	small-diameter, deep, pine; diam. 45, depth 15 mm
MDP	medium-diameter, deep, pine; diam. 55, depth 23 mm
MDE	medium-diameter, deep, eucalyptus; diam. 53, depth 15 mm
MSP	medium-diameter, shallow, pine; diam. 75, depth 15 mm

Other Surfaces

Flat Stump-Top	
Limestone Anvil (figure 258)	height 160 mm flat working surface 250x100 mm
Hardwood stake #1 (figure 257)	working face length 90 working face width max. 70, min. 30 mm working end h. max. 45, min. 15 mm
Hardwood stake #2	working face length 90 mm working face width max. 55, min. 45 mm working end h. max. 40, min. 25 mm

The Finishing Tools (Figure 261)

Abrasives:	limestone
	slate
	fine-grained igneous stone
	granite
	marble
	charcoal
	fine and coarse pumice

Burnishers: Polished haematite pebble
 Polished agate pebble

Chisel and Punch

Initially, two chisels were made from mild steel to test the functionality of the shapes: one with a straight-, or butt-end and the other with a curved working end. After a curved chisel was found to be better, one was made from sterling silver to use in the reconstructions (figure 259).

A steel centre-punch was used initially to test different hole-punching techniques. When these proved successful, a sterling silver punch was made for the reconstructions (figure 260).

Experiment 1: Bowl with Dropped Foot and Out-Turned Rim

This small copper bowl is made to ascertain the best techniques for sinking. To find out the best techniques to use for the major experiments to be carried out later, I need to discover how metal reacts to certain hammer-face profiles and hollow profiles. Since this exercise is primarily to test sinking techniques rather than to test Minoan equipment, I am using steel hammers which have rounded faces similar to those of Minoan stone hammering-tools (figure 281). I am also testing the effectiveness of burnishing with stone tools.

Aims

- 1: To find the most effective ways to use sinking to produce vessels.
- 2: To test the feasibility of creating a reflective surface on a vessel exclusively by burnishing the surface with stone tools.

Material

A copper disc 120 mm in diameter and 1.2 mm thick (figure 282, 0).

Process

1: Sink the disc into a bowl form (figure 282, 1).

Over the course of 20 hammering rounds interspersed with annealing, I experimented with different methods for creating a hollow form by stretching the material. The two methods tested were 1) forging the billet in hollow LSE with a hammer with a large, domed face (figure 281, top) and 2) sinking the billet into hollow SDP with a hammer with a small, domed face (figure 281, bottom). I found that sinking into the smaller hollow (SDP) with the small-faced hammer was much more effective for stretching the material. However, this sinking caused the hollow to become too deep to reach inside with the hammer (the handle obstructed access), and forging the material in the large hollow (LSE) helped to keep the hemisphere shallow enough to hammer the centre. This would not be an issue with an unhafted hammer.

In the last round, the base was flattened by tapping from the underside. The rim was also caulked slightly with the curved face of a planishing hammer to make the rim even. The result of these first 20 rounds was a bowl 35 mm high with a rim diameter of 120 mm, and the arc of the bowl was 160 mm.

2: Fold out the rim (figure 282, 2).

After one final anneal, the rim was caulked again. The rim was then folded out by tapping it over the edge of a stump with a planishing hammer.

3: Sink the dropped foot (figure 282, 3).

A hole with a diameter of 60 mm was cut in a piece of timber sheet 6 mm thick. The base of the bowl was placed over this hole and tapped down gradually to the desired depth. Another hammer with a long head had to be used for this in order to prevent the handle of the hammer from being obstructed by the wall of the vessel. Once again, this would not be so problematic with an unhafted hammer.

5: Burnish the surface.

I tested polished malachite, agate and haematite as burnishing tools on the inner surface of the bowl.

The finished bowl (figures 283 and 284) has an outer rim diameter of 130 mm and a total height of 35 mm. The out-turned rim is 10 mm wide and the dropped foot has a diameter of 55 mm and is 7 mm high. The material thickness of the rim is 0.9 mm and 0.5 mm half-way down the wall.

Results

1: The most effective technique for creating a deep, hemispherical form with thin walls using only hammers with curved faces (as Minoan stone tools have) is to alternate sinking with opening out the form by forging out the wall below the rim. Each round of sinking causes the form to become deeper and the rim to reduce in diameter. This in turn makes it difficult to access the inside vessel-surface during the next sinking round. By alternating rounds of sinking and forging, it is possible to continue stretching in the following round.

The most effective sinking method for this purpose is to use a hollow which is only slightly larger than the face of the hammer. A large hollow, while useful for creating a concave form, is not very effective for stretching and thinning material.

2: Agate and haematite burnishing tools create a highly polished surface very quickly but there is a tendency for ridges to be burnished into the surface. Malachite is less effective because it has a slight abrasive effect, creating a dull surface. It is apparent that the burnishing tool must be much harder than the metal.

Burnishing does not seem to be adequate for smoothing large irregularities on the surface. It appears that in order to create an absolutely smooth surface an abrasive may be required before burnishing.

Experiment 2: Bowl with Dropped Foot and Caulked Rim

I used stone hammers to make this small copper bowl. Most of the experimentation involved testing different hammer shapes and stone types.

Aims

- 1: Test different shapes of stone hammer for sinking a simple bowl.
- 2: Test the effectiveness of two stone types for hammering: basalt (a hard, very fine-grained igneous stone) and marble (a very soft metamorphosed sedimentary stone).
- 3: Test the means for making a heavily-caulked rim.
- 4: Find techniques for making a dropped foot with stone hammers.
- 5: Test fine pumice in solid form for finishing a vessel's surface.

Material

A copper disc 120 mm in diameter and 1.2 mm thick (**figure 285, 0**).

Process

1: Sink the disc into a bowl form and begin caulking to thicken the rim (**figure 285, 1**).

For the first 14 rounds, I alternated rounds of 1) sinking over hollow SDP using a smaller face of the basalt cobble with 2) one round of forging out the wall in hollow LSE or on a flat stump top with a large face of the cobble. The rim was caulked with the small face of the cobble after every second round to encourage it to stay thick and even. These rounds were interspersed with annealing. Forging out the material after each sinking round was necessary to prevent the small billet from becoming too concave to reach into with the cobble. I avoided sinking the centre too frequently in order to prevent this from becoming too thin. After these 14 rounds, the form was 105 mm in diameter, 36 mm deep and the arc of the wall 145 mm.

For rounds 15 to 28 (14 rounds), the same pattern was repeated, but I used the marble pestle for both sinking and forging since it was now difficult to access the inner walls with the basalt cobble. The pestle was much easier to use for heavy hammering than the cobble because it was less cumbersome to grasp in the hand. After these 14 rounds, the form was 118 mm in diameter, 45 mm high and the arc of the wall 164 mm.

In rounds 29 and 30 the base was flattened with the marble pestle on a stump top and the walls were shaped to a smooth curve in hollows SDP and LSE, causing the upper part of the wall to become vertical.

2: Finish caulking the rim (**figure 285, 2&3**).

With the bowl now formed, I continued the caulking of the rim with the side of the pestle. The rim tended to overlap more to the inside than the outside. The wall began to buckle underneath the blows. I attempted to harden the wall below the rim to prevent further buckling by forging it with the pestle on a stump-top. The wall continued to buckle with further caulking, so I ceased the caulking. The problem is probably a combination of the wall being too thin and copper being too soft. Harder material may be less problematic.

3: Sink the dropped foot (**figure 285, 2&3**).

As for Experiment 1, I sank the foot into a hole cut into a 6 mm sheet of wood. For this I used large granite pestle #1, using the large end to sink the centre of the foot and the small end around the edge. The bottom of the dropped foot was slightly curved, so I flattened it by tapping it from the bottom with the pestle.

4: Refine the profile.

The profile of the wall was made even by gently forging the wall from the inside with the marble pestle and the large face of the granite pestle against the curve of hollow LSE.

5: Finish the surface.

The caulked rim was fairly faceted. I found that the granite pestle was suitable for grinding these facets off, but it tended to leave deep scratches. Using a piece of fine pumice with water, I cut the orange-peel-textured surface of the underside of the bowl. The pumice worked, but was quite slow. In addition, the pumice tended to grind to dust very quickly, and the tools had to be constantly replaced. The scratches left were approximately the equivalent of 400 grade emery paper.

The finished bowl (**figure 286 and figure 287**) has an outer rim diameter of 116 mm and a total height of 40 mm. The caulked rim is 2.5 mm wide and the dropped foot has a diameter of 50 mm and is 5 mm high. The material thickness of the wall just below the rim is 0.9 mm and 0.5 mm half-way down the wall.

Results

1: A cobblestone is reasonably effective for stretching and thinning by sinking if it has a pointed face which can be used for sinking over a small hollow. It is more effective for general forging of larger areas. A pestle seems far more suitable for stretching and thinning material by sinking and is easier to manipulate since it is easier to grasp. It is also easier to direct the hammer blows with the pestle.

2: Basalt is a very effective material for hammering because of its durability. The stone did not suffer any chipping when used as a hammer. Marble is surprisingly durable; it does not seem to break readily, which I had assumed would be the case, but it does tend to gradually wear away with use.

3: The caulking aspect of this experiment was a failure since I was not able to produce a very broad rim such as are found on many Minoan vessels. The experiment indicates that the rim needs to be caulked more heavily before the wall becomes too thin.

However, the failure of this experiment may be due to the softness of copper, which is exacerbated by the thinness of the walls. This may not be so problematic with bronze.

4: A pestle seems to be a natural hammer with which to make a dropped foot since the striking-face can be directed immediately down into the base of a shallow vessel without a handle getting in the way.

5: Fine pumice is certainly effective as an abrasive, but is quite coarse. Finer abrasives would be required to bring the finish closer to a polish. Pumice is rather slow to use, however, because of its tendency to deteriorate very quickly.

Experiment 3: Hydria

The goal of this experiment is to create a hydria with similar dimensions and construction to the LM IIIA1 hydria from the Chania law-courts which I examined at the Chania Archaeological Museum (see §6.1.9). The hydria form was chosen for several reasons. Firstly, the various shapes required to make a typical four-section hydria represent most of the shapes found in the Minoan metal vessel corpus: thus a successful reconstruction of a hydria would provide results which may be applied to much of the Minoan vessel corpus.

The second reason for reconstructing a hydria is that it incorporates many techniques found in various Minoan vessels: sinking, raising and attaching appendages and joining sections with rivets, which entails making holes and manufacturing rivets. Thus, making a hydria allows me to test several different techniques on one vessel.

The last reason for making a hydria is that, since a hydria is composed of four sections, repetition of the techniques would be incorporated into the experiment, ensuring that I would be able to obtain reliable results based on repeated experiences.

Aims

- 1: Test replicated stone and wooden hammers for hammering large and complex shapes.
- 2: Test chisels for cutting sheet.
- 3: Test methods for punching holes.

- 4: Find methods for making rivets and riveting the seams of a vessel with Minoan equipment and resources.
- 3: Find methods by which handles might be attached to a vessel with Minoan equipment.
- 4: Find which Minoan finishing tools might produce a polished surface.

Experiment 3.1: Hydria Base Section

Material

A copper disc 231 mm in diameter and 2 mm thick (**figure 288, 0**).

Process

- 1: Sink the bowl form (**figure 288, 1**).

Over the course of 22 rounds interspersed with annealing, I completed rounds of sinking the billet over hollow SDP with a large granite pestle, following each round with opening out the outer 70 mm or so below the rim in hollow LSE with either the basalt cobble or the granite pestle. Every second round, I avoided sinking the centre to prevent it from becoming too thin. The rim tended to curl inwards with sinking, so I followed each sinking round with forging the rim out on a flat wooden stump with a granite pestle. After 14 rounds, I tried to alternate one round with the stone hammers with one round with a modern steel hammer because I was concerned about the damage being caused to my right hand from using the stone hammers. I found that this was soon impossible because the handle of the hammer prevented the head of the hammer from reaching into the deeper parts of the bowl.

I had hoped to stretch the arc to 390 mm, but I found that it was difficult to encourage the material from the rim to 50 mm down the wall to stretch as much as the centre, which stretched very quickly. Instead, I stopped trying to make the bowl larger when the arc had reached 343 mm with a rim of 225 mm.

- 2: Flatten the base (**figure 288, 2**).

In round 23, I flattened the base by tapping the centre down from the outside and tapping the material around the centre from the inside, creating a flat base 180 mm in diameter.

3: Straighten the sides (**figure 288, 3**).

The walls were straightened in one round by raising them with a large granite pestle over hardwood stake #1. This increased the rim diameter by 14 mm to 239 mm.

4: Create the base bulge, adapt base and reduce rim diameter (**figure 288, 4**).

Over the course of rounds 25 to 26, I continued raising in the wall, starting 20 mm up the wall from the base so that the base-bulge would be formed. The hammers tested for raising were the oak-branch mallet, the basalt cobblestone and a large granite pestle. The oak-branch mallet was useless since it was very difficult to aim and had a tendency to flex, minimising its effectiveness. The cobblestone was reasonably effective, but its large faces made it difficult to strike accurately. The granite pestle worked very well.

The base-bulge was encouraged out and smoothed somewhat by tapping it from the inside with the fine-grained igneous oblong and tapping the 'waist' above the bulge in from the outside.

I stopped bringing the walls in when the rim diameter reached 230 mm (**figures 289 and 290**). It seemed wise to make the middle section before finishing the base section so that the two could be adjusted to fit together.

Experiment 3.2: Hydria Middle Section

Material

A copper disc 265 mm in diameter and 2 mm thick (**figure 291, 0**).

Process

1: Sink the bowl form (**figure 291, 1**).

Over the course of 46 rounds, I sank the billet with large granite pestle #1 over hollow SDP, following each round with forging out the rim on a flat stump-top. As for the base section (Experiment 3.1), I avoided sinking the centre too frequently since it has a tendency to quickly become very thin.

At around the 40th round, tears began to form in the middle of the wall. To prevent these from opening up further with hammering I soldered them closed with hard silver solder. This was repeated after three more rounds because some of the tears began to open again.

2: Cut a hole in the base (figure 291, 2).

After the last round, I flattened the base somewhat in preparation for cutting the hole in the base. This was accomplished by tapping the base down from the outside. At this point, the bowl's rim was 305 mm in diameter and the arc 445 mm.

A hole was to be cut into the base which would subsequently be stretched out to fit into the base section. Using a curved chisel forged from mild steel and hammering with the basalt cobblestone, I cut a hole 70 mm in diameter according to calculations of what diameter the hole would need to be to fit into the base section of the hydria. The rough edge, which was approximately 0.7 mm thick, was cut back to smooth with the granite pestle.

3: Stretch out base to fit hydria base section (figure 292, 3&4)

From the new lower rim to 60 mm up the wall, I stretched out the lower rim and wall for 19 rounds by sinking over hollows SDP and MDP. Every three rounds, the material above the lower rim was forged flat on a stump-top (see figure 265). It soon became apparent that it would not be possible to stretch the lower base to the extent required, so a larger hole would need to be cut. At this point, the lower rim was 88 mm in diameter.

4: Cut a larger hole in the base (figure 292, 3&4).

A new hole with a diameter of 152 mm was cut in the base, again using the mild steel curved chisel and basalt cobblestone.

5: Stretch the lower rim to fit into the hydria base section (figure 292, 5).

Using the same methods as in step 3 above, the new lower rim was stretched out over five or six rounds, interspersed with annealing. When the diameter had reached 167 mm, I decided that the material was now too thin and fragile to continue stretching and decided that I would instead re-shape the base section of the hydria to fit the middle section (see figure 293).

6: Re-shape the base section to fit the middle section.

The base-bulge of the base section was reduced in diameter by tapping it in over air to 180 mm using the granite pestle. The wall above the bulge was subsequently raised in over seven rounds until the middle section sat neatly in the base section. This was carried out with a large granite pestle over stake #1 and interspersed with annealing.

Experiment 3.3: Hydria Shoulder Section

Material

A copper disc 300 mm in diameter and 3 mm thick (**figure 294, 0**).

Process

1: Sink bowl form (figure 294, 1**).**

In the first two rounds of sinking it became apparent that working a billet with such a large diameter and this thick (3 mm) would be much more physically demanding than the previous two hydria sections. In order to minimise damage to my hands and wrists, for the first 10 or so rounds of sinking I alternated between using a large marble pestle and using a steel hammer with a similarly-shaped striking face. Sinking was carried out initially over hollow MDP and then over MDE since the previous hollow had begun to deteriorate and split in parts.

As for the previous two vessel sections, this stage of transforming the billet into a large bowl consisted of two techniques per round: 1) sinking from centre to rim or rim to centre; 2) straightening the rim, in this case on a flat stump-top. After 34 rounds interspersed with annealing the rim diameter of the bowl was 335-340 mm, the height 160-170 and the profile 525-538 mm.

2: Shape the curve of the shoulder (figure 294, 2**).**

In round 35, I tapped down the base from the outside to flatten it and sank the material around the centre from the inside over hollow MDE with a large granite pestle to shape the curved shoulder of the hydria.

3: Cut a hole in the base for the neck (figure 295, 3&4**).**

A hole 85 mm in diameter was cut in the base using the sterling silver curved chisel illustrated in figure 259. The rough edges of the hole were smoothed with a piece of limestone, which proved very effective. The material thickness at the new rim was approximately 0.7 mm.⁵⁷³

4: Raise in the wall below the shoulder to create a taper (figure 295, 3&4**).**

Using a large granite pestle, raising of the wall below the shoulder was carried out for rounds 36 to 48 and interspersed with annealing. The last few of these

⁵⁷³ From here on, the new, small rim which will be joined to the top section of the hydria is considered the top of the shoulder section and will be called the upper rim, and the large rim which will be joined to the middle section will be referred to as the lower rim.

rounds focused on refining the profile of the wall so that the shoulder section would fit into the top of the middle section of the hydria.

5: Stretch out neck material (figure 295, 5).

In the last two rounds, the upper rim was stretched from a diameter of 85 mm to 100 mm by gently sinking it over hollow MDE with the granite pestle.

Experiment 3.4: Hydria Top Section

Material

A copper disc 170 mm in diameter and 3 mm thick (figure 296, 0).

Process

1: Sink the bowl form (figure 296, 1&2).

The bowl was formed over the course of 38 rounds. As for the previous vessel sections, this stage consisted of two techniques per round: 1) sinking from centre to rim or rim to centre; 2) straightening the rim on a flat stump-top. In rounds 39 and 40, the base was broadened with localised sinking. All of this shaping was carried out with a large granite pestle in hollow MDE. The resulting form had a rim diameter of 180 mm and a profile measurement of 265 mm.

2: Cut hole in base for join to shoulder section (figure 296, 1&2).

A hole 70 mm in diameter was cut into the base with the sterling silver chisel. The rough edge of the hole was ground smooth with the fine-grained igneous hammer.

3 & 4: Stretch the lower rim (figure 296, 3) and reduce the diameter of the upper rim (figure 296, 4).

In rounds 39 to 65, the lower rim was stretched by sinking over hollow MDE with a granite pestle and straightening the rim on a flat stump top. The upper rim was simultaneously raised inwards on stake #1, initially with the carver's mallet, but eventually with the large granite pestle when the material became too thick to move with the wooden mallet.

After these rounds, the pestle could not reach the lower rim from the inside any longer because the upper rim had narrowed. Instead, I continued to stretch it by hammering the rim from the lower end over the edge of a stump. After 14 more rounds, I stopped working on the lower rim.

5: Raise in the neck and stretch the lower half to fit onto the top of the shoulder section of the hydria (**figure 297, 5**).

Over the course of 16 further rounds, I continued to raise the upper half inwards. The neck was now too narrow to use stake #1, so I began to use stake #2, which is slightly narrower. As the neck approached the final diameter of 95 mm, I stretched the lower flare out by hammering it from the inside over the edge of a stump. The bottom of the neck was subsequently tapped in to form the smooth curve between the neck and the shoulder.

The final shaping of the lower part was accomplished by placing it over the upper rim of the shoulder section of the hydria and tapping it down into place.

6: Cut and fold over the rim (**figures 297, 6 and 298**).

The upper rim was quite uneven from the forming processes, so I attempted to cut it down using the sterling silver chisel. However, the material had become very thick from raising (3 mm), and even with repeated annealing and repeatedly sharpening the chisel, it was not possible to cut through the wall. I tried to use the mild steel curved chisel, but this too became blunt. After going around the rim seven times with little success, I had to resort to using a hardened tool-steel chisel instead. I subsequently cut back the rough edge with the fine-grained igneous stone hammer.

The rim was folded out horizontally over 11 rounds interspersed with annealing. This was accomplished by holding the neck against the flat end of a stake and forging out the rim with a large granite pestle (**figure 153**).

At this stage, the four sections of the hydria had been formed and fitted together (**Figure 299**). The next stages were to make the handles and join all the parts together.

The Handles

I did not attempt to reconstruct Minoan casting technology since this is a large topic better left for future studies. Handles were made for the hydria only to learn how to attach them to the body. They were roughly made by forging copper rod with modern equipment into the type of handle-shapes which are commonly found on Minoan hydrias: an upper strap-handle and a lower loop-handle (**Figure 300**).

Joining the Sections

The methods used to make holes in the hydria sections, to make the rivets and to join the sections were discussed in detail in §7.3.4, and will not be repeated here. I will only summarise the processes used and the order in which they were performed.

1: Make holes at the top of the base section, the top of middle section and the bottom of the top section.

A number of different methods for punching holes were tested (see §7.3.4).

Once these methods had been successfully tested on the different pieces, the remaining holes were made with an electric drill.

2: Make the rivets for the body (figure 275).

The rivets were cut from wire 4 mm in diameter and their first head formed with the techniques described in §7.3.4.

3: Join the base section to the middle section (**figure 301**).

As was discussed in §7.3.4, it was necessary to find a way to support the first head of each rivet whilst forging the second head closed. For this seam, I found the best way to accomplish this was to thread the rivet through the hole from the outside and lay the outside of the seam across the limestone anvil to close the second head with a granite pestle and with the basalt cobblestone.

4: Attach a repair patch to the wall over previous solder repairs (**figure 301**).

A piece of sheet copper was forged to 0.5 mm thick and cut into an appropriate shape to cover the part of the middle section which had tears in it from the shaping stages. It was cut using the curved sterling silver chisel and the basalt cobblestone and the rough edges smoothed with a fine-grained igneous stone. Holes were made around the perimeter of the patch and into the vessel wall with a power drill. Rivets were made from 2 mm copper wire and were fixed in place using the same method described in step 3 above.

5: Join the top section to the shoulder section (**figure 302**).

The rivets on this seam were fed through from the outside of the wall. Because of the tight curve between the neck and shoulder of the vessel, it was necessary to balance the work on the edge of the anvil so that the shoulder, upside-down, rested on the top of the anvil and the neck hung down the side. It was then possible to forge the inner rivet-heads flat using a granite pestle.

6: Make the rivets for the handles.

Using the same method as was used for the rivets of the seams, five rivets were made from copper wire 6 mm in diameter: three rivets for the upper handle and two for the lower handle.

7: Attach the lower handle to the bottom half and the upper handle to the top half (figure 301 and figure 302).

After making holes in the appropriate positions on the bottom half of the vessel, the rivets were fed through from the outside and the outside rivet-heads rested on the edge of the limestone anvil, one side at a time, so that the inside heads could be forged with a granite pestle.

The two upper rivets of the upper handle were difficult to attach. Because of the narrowness of the neck, it would not be possible to forge the heads closed from the inside. In any case, the out-turned rim and the shoulder of the vessel made it impossible to rest the outside wall against the anvil to accomplish this. The solution, described in §7.3.4 and illustrated in figure 278, was to pass the rivets through from the inside and feed a stake with a stone on top of it into the narrow neck so that the second head could be forged from the outside. The lower rivet of this upper handle was attached using the same method described in step three.

8: Join the upper and lower halves together (figure 303).

The final seam was the most difficult (see §7.3.4). The rivets were fed through from the outside and the outer rivet-head was rested on top of the anvil so that the inner heads could be forged from the inside by reaching through the neck. Both the basalt cobblestone and a granite pestle were tested for this; the basalt cobble was better in this case because its large working faces meant that it was not essential to aim accurately (which was difficult since it was not possible to see the inner heads while forging them). Because of the difficulty of balancing the large, heavy vessel in exactly the correct spot on the anvil, an assistant helped me by holding the vessel in place during the forging.

Unfortunately, due to a lack of foresight when making the holes on the outer part of this seam (the lower rim of the shoulder section) and the unevenness of the rim of the inner piece (the upper rim of the middle section), there was not enough overlap on some parts of the seam to provide a tight seal.

Finishing

1: Smooth the irregularities in the vessel walls.

The smoothing stages began before the sections were joined together. Firstly, large dents in the walls were gently tapped smooth from the inside or outside using the fine-grained igneous stone. Secondly, using polished stones, predominantly haematite, the walls were rubbed hard from the inside against the stump top, which pressed out many of the smaller irregularities.

2: Cut back the rough surface on the walls and produce a polished finish.

Various abrasive materials were tested on patches of the hydria (see §7.3.3). Coarse-grade materials were the limestone, granite, marble and coarse pumice. Fine-grade materials were the fine-grained igneous stone, fine pumice, slate and charcoal. I found that, from coarsest to finest, the cutting grades of these are in the following order: granite, limestone, coarse pumice, marble, fine pumice, fine-grained igneous stone, slate, charcoal. Naturally, the order of these might alter slightly with materials from different regions. None of the finer abrasives were capable of producing a highly-polished finish, although charcoal does produce a reasonably reflective satin finish. The only means I could find for producing a high polish is burnishing with a hard polished stone, in this case haematite. Since the surface area of the hydria is very large, I sought the assistance of two other experienced metalsmiths for this stage.⁵⁷⁴

The completed hydria (**figure 304**) is 440 mm high. The diameter of the rim is 117 mm, the base 180 mm and the shoulder 350 mm. The material thickness is extremely variable. The material at the rim is 2 mm thick. The thinnest parts of the wall, which are at the lower rim of the top section, the upper rim of the shoulder section and the middle of the wall of the middle section, are approximately 0.4 mm thick, making them very fragile. The thickest material is 3 mm in the wall of the neck. The average material thickness of the rest of the vessel is approximately 1 mm. This is thicker than the average material thickness of the vessels examined and described in Chapter Six, the walls of which tend to be no thicker than 7 mm on average.

⁵⁷⁴ I am indebted to Mary Dearden and Lan Nguyen-hoan for this assistance.

Results

1: For sinking, pestle forms are the most effective of the replicated tools. For raising, a mallet made from the angle of a tree-branch (see §4.4.1 and figure 142) is not effective but a carver's mallet is effective on thinner sheet. A pestle form is effective for raising thin and thick sheet.

2: A curved chisel is very effective for neatly cutting sheet. A low-tin bronze chisel would be hard enough to cut thin sheet but thicker material would probably require the use of a high-tin bronze.

3: Several methods can be used to punch holes in sheet (see §4.6.2). All of these are variations on simply hammering the end of a punch through the material.

4: Rivets can be made by just cutting wire or rod and forging a head using a pestle on a wooden surface. A jig for holding the rivet speeds the process but is not a necessity. Closing the second rivet-head into a seam generally requires a stone anvil and a stone hammer; more complex seams may require some improvisation with the available tools to support the first head on a stone surface.

3: The means for attaching handles to vessels are similar to those required for closing seams.

4: Limestone, granite, and coarse pumice are too coarse for surface finishing, though they are excellent for other cutting processes. Fine-grained igneous stones are particularly effective for cutting back a metal surface since they cut well but do not leave very deep scratches. Slate and marble with water are excellent intermediate abrasives and charcoal a very effective fine abrasive. For producing a high polish I found that none of these abrasives were fine enough and burnishing with hard polished stones seems to be the only means.

Experiment 4: Copper One-Handled Basin (Initial Stages)

The primary purpose of this exercise is to test the effectiveness of a pi-shaped hearth with a blowpipe for annealing a billet. Some preliminary tests are also undertaken in anticipation of the next experiment, the making of a silver one-handled basin. In particular, I need to ascertain how to produce the wide, thickened rim for such a vessel. In Experiment 2 above, I found that caulking the rim after the vessel had been formed was impractical since the force of the hammer blows on the rim caused the thin wall

underneath to collapse. Thus it seems that it would be better to begin the caulking much earlier, before the walls become very thin. In this experiment, the rim is caulked heavily before the sinking begins in order to discover how this technique would work for creating a heavily-thickened rim on a one-handled basin. Since it is only the initial stages of creating such a vessel which is being tested, the vessel will not be completed.

Aims

- 1: Use a pi-shaped hearth with a blowpipe to anneal a billet.
- 2: Caulk the rim before sinking the disc to see if this is an effective method for creating a heavily thickened rim with an overhang.

Material

A copper billet 3 mm thick. The billet has an extension at the edge for the handle, so that the billet is the shape of a ping-pong paddle (**figure 305**). The diameter of the disc-section is 150 mm and the length of the handle is 150 mm, making a total length of 300 mm. The billet was annealed with a gas torch in preparation for this experiment.

Process

- 1: Caulk the rim.

The billet was held vertically on a flat stump-top so that the rim of the billet rested on the stump. Using a granite pestle, I caulked around the circumference of the rim and one-quarter of the way up the handle. I continued caulking until the material was too hardened to continue. The billet was annealed (with a gas torch) and the process repeated. Using this method, it was easy to quickly create a heavily-thickened rim with an overhang on the flat billet.

- 2: Anneal.

Using the pi-shaped hearth and the aluminium blowpipe, the billet was annealed in the manner described in §7.3.1, quenched in a solution of salt and vinegar and rinsed.

- 2: Sink and caulk.

Over two rounds, I sank the billet with a granite pestle over hollow MDE. The first round began from just under the thickened rim and finished in the centre

and the second round was the reverse of this. I very quickly discovered that it was virtually impossible to thin the material just below the thickened rim since the rim obstructed the hammer blows. After sinking, I caulked the rim again. Annealing in the pi-shaped hearth and sinking and caulking were repeated twice more, resulting in a shallow dish with a heavily-thickened rim and an upright handle (**figures 306 and 307**).

Results

1: The pi-shaped hearth and blowpipe was very effective for annealing the billet. A strong wind blowing over the fuel also proved effective for increasing the temperature of the fuel.

2: Caulking the rim of the billet before sinking and in the early stages of forming the vessel is not a method that would have been used to create Minoan vessels. It was impossible to stretch the material just below the rim because the rim obstructed the hammer-head from reaching this material. The walls of the examined Minoan vessels of this type (see §6.1.10 and §6.1.11) were very thin: a similar thickness to the lower parts of the walls. This indicates that the walls must have been made thin well before the rims were caulked.

Experiment 5: Sterling Silver One-Handled Basin

The goal of this exercise is to create a small one-handled basin (*BKMK* type 32A) from sterling silver. The basin will have a dropped foot and a heavily thickened rim.

Aims

1: Test the viability of stone hammers for working sterling silver, which is closer in hardness than copper is to the bronzes used to make Minoan vessels.

2: Test whether it is possible to perform spiral-forging with a stone hammer on a stone anvil.

Material

A sterling silver billet 3 mm thick. The billet has an extension at the edge for the handle, so that the billet is the shape of a ping-pong paddle (**figure 308.0**). The diameter of the disc-section is 110 mm and the length of the handle is 130 mm, making a total length of 240 mm.

Process

1: Forge out the disc-section of the billet to 140 mm in diameter (**figure 308, 1: top view and side view**).

I forged the billet on the limestone anvil with a large granite pestle, hammering in lines radiating from the centre of the disc. The billet was annealed after each round and hammering alternated between the two sides to keep the billet relatively flat. The diameter expanded by approximately 2 mm per round.

I continued forging for seven rounds and expanding the diameter to 125 mm, but my right hand and wrist were getting badly damaged. At this point, since the experiment had indicated that this process is viable with a stone hammer and anvil, I completed the last six rounds with a steel hammer on a steel anvil to prevent further damage to myself. These tools increased the diameter by 2.5 to 3 mm per round.

2: Create a concave form with spiral-forging and begin caulking the rim (**figure 308, 2**).

I attempted to transform the disc-section into a concave form by spiral-forging on the limestone anvil with a large granite pestle. I quickly found that the process is unsuitable for stone tools; perhaps the surfaces of the hammer and the anvil must be much smoother and the material much harder. The form was made by sinking instead.

After three rounds of sinking with a large granite pestle over hollow MDE, I caulked the rim partially, initially with a large granite pestle, but I found that the hammer blows were easier to control with the small granite pestle. I continued sinking and caulking for seven rounds, annealing as required.

3: Complete final shaping of the basin and finish caulking the rim (**figure 309, 3**).

Once a hemispherical shape with a large enough profile had been formed, I flattened the base with a granite pestle to achieve the correct shaping on the base and walls. I continued to caulk the rim until the width reached 6 mm.

4: Begin bending the handle into shape.

The handle was bent into shape after the basic form of the vessel had been created because if it had been formed before the basin had been finished then it would have made it impossible to work on the part of the wall below the handle. However, I began shaping the handle before sinking the foot and completing the caulking of the rim because bending the handle would require bending, annealing and bending again. I did not want to have to anneal the vessel after I had dropped the foot since this would weaken the basin, making the wall soft and vulnerable to denting.

I began forming the ring-form of the handle by sinking the underside into hollow MDE with a large granite pestle. I avoided hammering the upper surface because this would have damaged the surface of the handle. I noted that the handle of the Piskokephalo one-handed basin (§6.1.10) could not have been hammered because this would have damaged the cast decoration.

5: Drop the foot by sinking; refine the profile of the foot (**figure 309, 4&5**).

The foot was dropped after the caulking had been completed because I was concerned that continuing to caulk the rim after the foot had been dropped would result in the collapse of the foot and of the wall above it as had occurred in Experiment 3.2. I dropped the foot into hollow MDE with a large granite pestle and the small granite pestle. The resulting foot was fairly rounded, so I flattened the base by sinking it from underneath with a large granite pestle. I subsequently sharpened the profile of the foot with the sterling silver chisel, striking it with the basalt hammer gently to prevent cutting into the material.

6: Finish bending the handle into shape (**figure 309, 4&5**).

Repeating the technique described in step 4, I continued shaping the ring-handle. The final ring-shape was created by gently tapping the handle over a wooden rod (a broomstick) with a rawhide hammer, avoiding damage to the upper surface.

7: Finish the surface.

Due to time constraints, I was unable to complete finishing the surface of the basin before this study was sent to be printed. A fine-grained igneous stone was used to cut back the rough surface left from hammering and this was followed by cutting back with slate. The last stage, illustrated in **Figure 310**, shows the satin finish left by cutting with charcoal and water.

The rim diameter of the finished vessel is 125 mm, the basin height 30 and the total height 75 mm. The dropped base is 60 mm in diameter and 5 mm high.

Results

1: I did not notice a substantial difference between working copper and working sterling silver with stone hammers.

2: It does not seem to be possible to perform spiral forging with the stone hammers and stone anvil which were used for this study. Moreover, it seems to be a process which one would not naturally think to use with these tools. It seems unlikely that this technique would have been used in the process of making Minoan metal vessels.

Summary of the Results

Hammering Techniques

- A thin-walled, hemispherical form of any size can be made with sinking using found-faced stone tools. The rim and the wall below it may need to be forged straight after each round.
- To produce the wide thickened rims found on some Minoan vessels, most notably on *BKMK* type 32A one-handled basins, the rim must be caulked regularly throughout the shaping processes of the vessel, but not heavily during early shaping stages.
- Spiral-forging a billet to create a concave form does not seem to be possible with Minoan tools.

Hammer Types and Hammer Materials

- The most effective sinking technique requires a hollow which is only slightly larger than the hammer-face.
- Pestle-shaped stone tools are an excellent shape for sinking, raising and forging.
- Cobblestone hammers are suitable for general forging and sinking of large areas but not so much for precision work. They are not very suitable for raising but are excellent for striking other tools.

- The type of stone a hammer is made from does not seem necessarily to affect its functionality. Hard igneous materials such as basalt, fine-grained stones and granite are hard-wearing and last for a long time, although granite may fracture with repeated stress. Softer materials such as marble work well but tend eventually to deteriorate.
- Stone hammers were probably as suitable for producing bronze vessels as they are for copper vessels.
- A wooden mallet in the form of a carver's mallet is suitable for raising thin material. Once the material is thicker than approximately 2 mm, it becomes very difficult.
- A wooden mallet made from the angle of a branch is not suitable for vessel-making.

Finishing Tools and Processes

- To produce a high polish, the most effective method is to follow three or more grades of abrasive with burnishing.
- Burnishing tools must be much harder than the metal being worked. Haematite and agate work very well.
- Limestone, granite and coarse pumice are coarse abrasives well-suited to cutting processes which would today usually be performed with a coarse file such as grinding back sharp sheet edges.
- Fine-grained igneous stones are excellent for cutting processes which would today usually be performed with a fine file such as cutting back rough surfaces without leaving deep cuts.
- Slate, fine pumice and marble lubricated with water are suitable for the kind of intermediate cutting that today would be performed with 400 to 600 grade emery paper.
- Charcoal lubricated with water is a fine abrasive approximately equivalent to 1200 grade emery paper.

Other Tools and Processes

- A Minoan pi-shaped hearth would have been more than adequate for annealing vessels during their manufacture. A draft supplied by a single blowpipe or a strong wind is all that is required to speed up the annealing process.
- Curved chisels are well suited to neatly cutting sheet metal.
- Low-tin bronze chisels and punches may have been adequate for working metal sheet, but thicker material probably required high-tin bronze tools.
- Closing the second head of a rivet probably usually requires a stone anvil to provide enough resistance to forge the second head.

Catalogue of Minoan Metal Vessels

For this study, I compiled a database of every Minoan metal vessel that I was able to locate. The bulk of the data was drawn from Catling's *Cypriot Bronzework in the Mycenaean World*, Popham, Catling and Catling's "Sellopoulo Tombs 3 and 4, Two Late Minoan Graves near Knossos, Davis's *The Vaphieo Cups and Aegean Gold and Silver Ware*, Matthäus's *Die Bronzegefäße der kretisch-mykenischen Kultur*, Tsipopoulou's "Minoan Metal Vessels and Vases" and Hakulin's *Bronzeworking on Late Minoan Crete*.⁵⁷⁵ The database consists only of vessels which are complete enough to determine their type; it does not include unidentifiable fragments.

The table presents this database in an abbreviated form, since the database itself is too complex to compile in table format. Consequently, only basic information about each vessel is supplied here. The data for the vessels is arranged into columns, explained below.

Period

For most of the bronze vessels, where there are differences noted for the period of any one vessel, the period noted by Hakulin was used since this is the most recent publication. Dates marked with T in superscript are those given by Tsipopoulou in the catalogue of the Mitsotakis Collection.⁵⁷⁶ Superscript ANM indicates a date supplied by the Ayios Nikolaos Archaeological Museum. Superscript C refers to Catling's *CBMW*.⁵⁷⁷ Dates for precious vessels are those listed by Rehak.⁵⁷⁸

Site and Context

The details in the site and context columns refer to the sites and buildings or graves from which the vessels were recovered.

⁵⁷⁵ Catling, *CBMW*; Popham, Catling, and Catling, "Sellopoulo"; Davis, *AGSW*; Matthäus, *BKMK*; Tsipopoulou, "Minoan Metal Vases and Vessels"; Hakulin, *BLMC*.

⁵⁷⁶ Tsipopoulou, "Minoan Metal Vases and Vessels."

⁵⁷⁷ Catling, *CBMW*.

⁵⁷⁸ Rehak, "Aegean Art Before and After the LM IB Cretan Destructions."

Type

The type numbers are from Matthäus's typology in *BKMK*.⁵⁷⁹ Those marked with an asterisk are those which, since they were either not included in or were published after Matthäus's publication, I have attempted to categorise by the typology. Some which I have described here either did not fit the typology or were not published with enough information to determine their type. Matthäus's types referred to here are as follows:

1. cauldrons with walls made from multiple sections (Kessel mit mehrteiliger Wandung)

1A. Variant A

1B. Variant B

1C. Variant C

4. steep-sided pans (Steilwandige Kessel)

4A. Variant A

4B. Variant B

4 *Varia*. Variation

5. tripod cauldrons: Middle Minoan Precursor (Dreifußkessel: mittelminoische Vorläufer)

6. cylindrical tripod cauldrons with horizontal handles (Zylindrische Dreifußkessel mit waagerechten Henkeln)

tripod cauldrons, unidentifiable form (Dreifußkessel unbestimmbarer Form)

7. tripod cauldrons with a rounded base and offset rim (Rundbodige Dreifußkessel mit abgesetztem Rand)

7A. with ring-handles (mit Ringhenkeln)

9. three-footed pans (Dreifußige Pfannen)

10. two-handled basins (Zweihenklige Becken)

10A. Variant A

10B. Variant B

10C. Variant C

10E. Variant E

⁵⁷⁹ Matthäus, *BKMK*.

unidentifiable vessels and fragments (Unbestimmbare Gefäße und Fragmente)

12. small basins with curved walls and a rounded base (Kleine Becken mit geschwungener Wandung und rundem Boden)

13. large pans with a vertical nozzle-grip (Große Pfannen mit senkrechtem Tüllengriff)

13A. Variant A

15. small pans with a vertical, solid grip (Kleine Pfannen mit senkrechtem massivem Griff)

20. early hydria types (Hydrien frühen Typs)

21. late hydria types (Hydrien späten Typs)

unknown hydria types (Hydrien unbekannten Typs)

22. pitchers with a neck-bulge and embossed decoration (Kannen mit Halswulst und getriebener Verzierung)

22A. Variant A

pitcher fragments (Kannenfragmente)

24. piriform pitchers with a shoulder-band (Piriforme Kannen mit Schulterband)

25. pitchers of the LM/LH III A periods: variation (Kannen der Periode SM/SH III A: Varia)

piriform pitchers with a narrow neck-bulge (Piriforme Kanne mit schmalem Halswulst)

ovoid pitchers with transverse handles and a decorated shoulder-band (Ovoide Kanne mit Querhenkeln und verziertem Schulterband)

26. two-part, undecorated pitchers with a torus-foot (Zweiteilige unverzierte Kannen mit Torusfuß)

27. pitchers with a bird-protome (Kanne mit Vogelprotome)

28. small, bulbous pots (Kleine bauchige Kannen)

29. pitcher with a ring-stand (Kanne mit Standring)

30. wide-mouthed, beak-spouted pitchers (Weitmundige Schnabelkannen)

31. beak-spouted pitchers (Schnabelkannen)

- 32. large, one-handled, broad-rimmed bowls (Große einhenklige Breitrandschalen)**
- 32A. Variant A: broad-rimmed bowls of a single piece (Einteilige Breitrandschalen)**
 - 32B. Variant B: simple broad-rimmed bowls with a riveted-on handle (Schlichte Breitrandschalen mit genietetem Henkel)**
 - 32C. Variant C: broad-rimmed bowls with a lead-lined rim (Breitrandschalen mit bleigefüttertem Rand)**
 - 32D. Variant D: broad-rimmed bowls with a copper-lined rim (Breitrandschale mit kupfergefüttertem Rand)**
 - 32E. Variant E: relief-decorated broad-rimmed bowl (reliefverzierte Breitrandschalen)**
- 33. one-handled cups (Einteilige Tassen)**
- 35. round-based cups with a lateral spout and related forms (Rundbodige Tassen mit seitlichem Ausguß und verwandte Formen)**
- 36. knob-handled cups (Knopfhenkeltassen)**
- 37C. cups with a narrow band-handle (Tasse mit schmalem Bandhenkel)**
- 37D. cups with transverse handles (Tasse mit Querhenkeln)**
- 38. one-handled, conical beakers (Einhenklige konische Becher)**
- 38B. Variant B: beakers of the 'Vapheio' type (Becher des Typs Vaphio)**
 - 38BIV. Variant B: beakers of the 'Vapheio' type: high conical beaker without a ridge (Becher der Typs Vaphio: hohe konische Becher ohne Wulst)**
- 40. beakers with a spout (Becher mit Ausguß)**
- 43. kylikes (Kylikes)**
- 44. lekanai: precursors (Lekanai: Vorläufer)**
- 45. lekanai (Lekanai)**
- 45A1. Variant A1: lekanai with simple horizontal handles (Lekanai mit waagerechten schlichten Henkeln)**
 - 45A2. Variant A2: lekanai with horizontal handles and a spout (Lekanai mit waagerechten Henkeln und Ausguß)**

- 45B1.** Variant B1: lekanai with knob-handles (Lekanai mit Knopfhenkeln)
- 45B2.** Variant B2: lekanai with knob-handles and a spout (Lekanai mit Knopfhenkeln und Ausguß)
- ?lekanai with moulded handle-ornaments (Lekane (?) mit plastischem Henkelschmuck)
- 46.** Middle Minoan two-handled bowls (Mittelminoische zweihenkligte Schale)
- 47A.** hemispherical bowls (Kalottenschalen)
- 49B.** bowls with a curved base and out-turned rim (Schale mit auf gewölbtem Boden und umgeschlagenem Rand)
- 49C.** moveable stirrup-handle (Bewegliche Bügelhenkel)
- 50.** straight-walled bowls with a dropped foot (Geradwandige Schalen mit eingetiefter Standfläche)
- 51.** handleless conical bowls (Henkellose konische Schalen)
- 57B.** ladles with a solid grip and a loop (Schöpfer mit massivem Griff und Endschlaufe)
- 57C.** ladles with a loop-handle (Schöpfer mit Schlaufenhenkel)
 - 57C1.** with a hemispherical bowl (mit halbkugeliger Schale)
 - 57C2.** with a foot and bent wall (mit Standfläche und Wandungsknick)
- 58A.** lamps with a riveted-on rod-grip (Lampe mit genietetem rundstabigem Griff)
- 58B.** lamps with a band-grip (Lampen mit Bandgriff)
 - 58B1.** with a rounded vessel-body (mit gerundetem Gefäßkörper)
 - 58B2.** with a straight-walled vessel-body (mit geradwandigem Gefäßkörper)
- 59A.** large braziers with a nozzle-grip (Große Räucherbecken mit Tüllengriff)
- 60.** sieves (Siebe)

Metal

Metal is only listed for precious metal vessels and copper or bronze vessels for which analyses have indicated the metal or alloy. The exact compositions of these and the sources for the analyses are supplied in Appendix 2. Others which have not been tested

and for which no metal type is indicated in the table are unknown and presumed to be copper or bronze. The metal listed only indicates that which the vessel body is made from. In some cases, the vessel may have inlays of other metals, but these are not listed here. Elemental metals are indicated by their chemical symbol and bronze by “br”. Metal types marked with an asterisk are alloys which I have determined visually during the examinations undertaken for this study.

Collection

Collection numbers are supplied where available. Museum names are abbreviated as follows:

ANM	Ayios Nikolaos Archaeological Museum
AshM	Ashmolean Museum
BSA	British School at Athens
CM	Chania Archaeological Museum
HM	Heraklion Archaeological Museum
MusPig	Museo Pigorini

BKMK

This column lists the catalogue numbers of those vessels in *BKMK*.

BLMC

This column lists the catalogue numbers of those vessels in *BLMC* (Appendix V.2).

Other Ref.

This column lists the catalogue numbers of those vessels in *AGSW* and in Tsipopoulou’s “Minoan Metal Vases and Vessels” (MMVV).

Table 5. Catalogue of Minoan Metal Vessels

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
1	EM IIB-III	Mochlos	Tomb 6	*33	Ag	ANM			AGSW p. 95, n. 265
2	EM II-III	Mochlos	Tomb 6	*47A?	Ag	HM			AGSW no. 11
3	MM	Kalathiana	House Delta	10A		HM 1491	105		
4	MM	Gournia	House Tomb 2	lobed kantharos	Ag	HM 201			AGSW no. 12
5	MM	Tylissos	House	10A		HM	114		
6	MM II	Malia	Quartier M	5		HM 3069	41		
7	MM II	Malia	Quartier M	5		HM 3068	42		
8	MM II	Malia	Quartier M	5			43		
9	MM II	Malia	Quartier M	9		HM 3070	102		
10	MM II	Malia	Quartier M	46			413		
11	MM II	Malia	Quartier M	49C			425		
12	MM IIIB	Malia vicinity	property of Grammatikakis	6		HM	61	784	
13	MM IIIB	Malia vicinity	property of Grammatikakis	10A		HM 2194	111	785	
14	MM IIIB	Malia vicinity	property of Grammatikakis	10B	Cu	HM 2195	117	786	
15	MM IIIB	Malia vicinity	property of Grammatikakis	10B		HM 2196	118	787	
16	MM IIIB	Malia	property of Grammatikakis	20		HM	211	788	
17	MM IIIB	Malia	property of Grammatikakis	32E		HM 2193	327	791	
18	MM IIIB	Malia	property of Grammatikakis	35		HM	347	792	
19	MM IIIB	Malia	property of Grammatikakis	32C		HM	320	790	
20	LM IA	Knossos	Basement Cell by Stepped Portico	10A		HM	106	769	
21	LM IA	Knossos	Basement Cell by Stepped Portico	10A		HM	107	770	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
22	LM IA	Knossos	Basement Cell by Stepped Portico	10A		HM	108	771	
23	LM IA	Knossos	Basement Cell by Stepped Portico	10A		HM	109	772	
24	LM IA	Knossos	Basement Cell by Stepped Portico	10A		HM	110	773	
25	LM IA	Knossos	Basement Cell by Stepped Portico	32A		HM	310	775	
26	LM IA	Knossos	Basement Cell by Stepped Portico	32B		HM	314	776	
27	LM IA	Knossos	Basement Cell by Stepped Portico	32B		HM	315	777	
28	LM IA	Knossos	North-West Treasure House	32A		HM	309	760	
29	LM IA	Knossos	North-West Treasure House	32E		HM	324	761	
30	LM IA	Knossos	North-West Treasure House	32E		HM 845	326	763	
31	LM IA	Knossos	North-West Treasure House	32E		HM 844	325	762	
32	LM IA	Knossos	Basement Cell by Stepped Portico	30		HM 2074	301	774	
33	LM IA	Malia	property of Grammatikakis	30		HM 2192	302	789	
34	LM IA	Knossos	North-West Treasure House	22A		HM 843	252	759	
35	LM IA	Malia	Quartier A, Maison de la façade à Redans, Room 15	6		HM	58	795	
36	LM IA	Knossos	Basement Cell by Stepped Portico	32A or B		HM	332	778	
37	LM IA	Knossos	Basement Cell by Stepped Portico	32A or B		HM	333	779	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
38	LM IA	Knossos	Basement Cell by Stepped Portico	44	br	HM 2075	370	780	
39	LM IA	Malia	House Delta-beta, Room 8	1B		HM	2	798	
40	LM IA	Knossos	North-West House	6		HM	55	764	
41	LM IB	Tylissos	House A, Magazine 4 (β)	1B		HM	3	811	
42	LM IB	Tylissos	House A, ?Magazine 4 (β)	1A	Cu	HM	1	810	
43	LM IB	Tylissos	House A, Magazine 4 (β)	1B		HM	4	812	
44	LM IB	Tylissos	House A, Magazine 4 (β)	1C		HM	14	813	
45	LM IB	Mochlos	Block B, Room C	10A	Cu	HM 1581	112	799	
46	LM IB	Mochlos	Block B, Room C	10A		HM 1582	113	800	
47	LM IB	Zakros	Room 12	6		HM 2068	49	815	
48	LM IB	Zakros	Tomb 1962	10C		HM Z/62/2607	123	822	
49	LM IB	Zakros	palace, Room 42	6		HM	50	816	
50	LM IB	Zakros	palace, Room 44	6		HM	51	817	
51	LM IB	Zakros	palace, Room 45a	6		HM	52	818	
52	LM IB	Zakros	palace, Room 45a	6		HM	53	819	
53	LM IB	Zakros	palace, Room 48	6		HM	54	820	
54	LM IB	Zakros	palace, Room 45a	22 (indeterminable fragment)		HM	262	823	
55	LM IB	Zakros	palace, Room 25	32E		HM (exhibition)	323	824	
56	LM IB	Mochlos	Block B, Room C	32E		HM 1578	328	801	
57	LM IB	Mochlos	Block B, Room C	32		HM	334	802	
58	LM IB	Mochlos	Block B, Room C	32		HM	335	803	
59	LM IB	Palaikastro	Block N, Room 9	49B		HM	424	924	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
60	LM IB	Zakros	palace, Room 45a or b	57 (type unknown)			451	825	
61	LM IB	Zakros	palace, Room 28	58A		HM	453	826	
62	LM IB	Zakros	palace, Room 45a	59A		HM	466	827	
63	LM IB	Zakros	palace, Room 27	60		HM	470	828	
64	LM IB	Zakros	palace, Room 45a	60		HM	471	829	
65	LM IB	Zakros	House A, Room P	60		HM	472	830	
66	LM IB	Mochlos	Building B2	*32				1739	
67	LM IB	Mochlos	Building B2	*32				1741	
68	LM IB	Mochlos	House C7	?vase				1757	
69	LM IB	Mochlos	House C4	*10A				1726	
70	LM IB	Mochlos	House C3					1742	
71	LM IB	Mochlos	House C7					1756	
72	LM IB	Mochlos	House A2	*44	br			1725	
73	LM IB	Mochlos	Building B2	*32				1740	
74	LM IB	Mochlos	Building B2	*32				1737	
75	LM IB	Mochlos	Building B2	*32				1736	
76	LM IB	Mochlos	House A2	bowl w/ dropped foot and everted rim	br			1724	
77	LM IB	Mochlos	Building B2	*32				1738	
78	LM IB	Zakros	storeroom in west wing of palace	ewer	Ag	HM 962			AGSIV no. 13
79	LM IB	Knossos	South House	ewer	Ag	HM 404			AGSIV no. 14
80	LM IB	Knossos	South House	bowl	Ag	HM 403			AGSIV no. 15
81	LM IB	Ayia Triada	Lightwell 9					1789	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
82	LM IB	Ayia Triada	Lightwell 9					1787	
83	LM IB	Ayia Triada	Lightwell 9					1786	
84	LM IB	Ayia Triada	Lightwell 9					1788	
85	LM IB	Ayia Triada	Lightwell 9					1791	
86	LM IB	Ayia Triada	Lightwell 9					1790	
87	LM IB	Ayia Triada	Hall 12					1792	
88	LM IB	Palaikastro	Room 14, Block ξ	20		HM	212	923	
89	LM IB	Mochlos	Tomb 12	38B			357	807	
90	LM IB	Mochlos	Tomb 12	47A		HM	415	809	
91	LM IB	Ayia Triada	?bathroom	6		HM	48	1782	
92	LM IB	Gournia	Room F 41	10 (indeterminable fragment)		HM	158	833	
93	LM IB	Gournia	road south of Room G15	49C		HM 617	426	834	
94	LM IB	Gournia	Area F 18	6		HM	47	832	
95	LM IB	Gournia	Area B6	6		HM 605	46	831	
96	LM IB	Knossos	South House	bowl w/ everted rim	Ag	HM 401			AGSW no. 16
97	LM IB	Knossos	South House	bowl w/ dropped foot and everted rim	Ag	HM 402			AGSW no. 17
98	Neopalatial	Knossos	house SE of the South House	20		HM 2079	210	768	
99	Neopalatial	Knossos	house SE of the South House	6		HM	56	766	
100	Neopalatial	Knossos	house SE of the South House	6		HM	57	767	
101	Neopalatial	Knossos	house SE of the South House	4A		HM	32	765	
102	Neopalatial	east Crete		6		AshM 1967.1213	69	934	
103	Neopalatial	Crete		10C		AshM 1967.1216	124	935	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
104	Neopalatial	Rethymno	near Rethymno	20		Rethymno	214	928	
105	Neopalatial	east Crete		13A		AshM 1967.1214	166	936	
106	Neopalatial	east Crete		13A		AshM 1967.1215	167	937	
107	Neopalatial	Tylissos	settlement	38B		HM	358	814	
108	Neopalatial	Mochlos	Tomb 7	44		HM	369	808	
109	Neopalatial	Kouphi		20		Rethymno	213	927	
110	Neopalatial	Mochlos	Tomb 9	33		HM	338	804	
111	Neopalatial	Mochlos	Tomb 9	33		HM	339	805	
112	Neopalatial	Mochlos	Tomb 9	33		HM	340	806	
113	LM II	Knossos	Unexplored Mansion	10E		HM	149	781	
114	LM II	Katsamba	Tomb B	47A		HM	414	932	
115	LM II	Knossos	Unexplored Mansion	59A		HM	467	782	
116	LM II	Archanes	grave north of Tholos B	33	Ag	HM 1011	p. 219, no. a		AGSW no. 20
117	LM III ^{ANM}	Piskokephalo		32A	*br	ANM 54	311	930	
118	LM IIIA1	Zapher Papoura	Tomb 14p	7A		HM 1081	72	879	
119	LM IIIA1	Zapher Papoura	Tomb 14c	12			165	881	
120	LM IIIA1	Zapher Papoura	Tomb 14k	4B		HM 1086	37	878	
121	LM IIIA1	Phaistos	Tombe dei Nobili	10E		HM	150	870	
122	LM IIIA1	Zapher Papoura	Tomb 14g	21		HM 1088	241	883	
123	LM IIIA1	Zapher Papoura	Tomb 14l	31		HM 1090	303	884	
124	LM IIIA1	Phaistos	Tombe dei Nobili, Tomb 8	28		HM	297	873	
125	LM IIIA1	Zapher Papoura	Tomb 14e	15		HM 1091	178	882	
126	LM IIIA1	Phaistos	Kalyvia Necropolis, Tomb 8	15		HM	177	872	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
127	LM IIIA1	Sellopoulo	Tomb 4, Burial I	6		HM	66	905	
128	LM IIIA1	Sellopoulo	Tomb 4, Burial I	6	br	HM	65	904	
129	LM IIIA1	Sellopoulo	Tomb 4, Burial I	6		HM	68	906	
130	LM IIIA1	Sellopoulo	Tomb 4	6		HM	67	922	
131	LM IIIA1	Sellopoulo	Tomb 4, Burial I	10A		HM	115	907	
132	LM IIIA1	Sellopoulo	Tomb 4, Burial I	10E		HM	151	908	
133	LM IIIA1	Sellopoulo	Tomb 4, Burial III	4A		HM	33	919	
134	LM IIIA1	Sellopoulo	Tomb 4, Burial I	32A		HM	312	913	
135	LM IIIA1	Sellopoulo	Tomb 4, Burial I	27	br	HM	296	911	
136	LM IIIA1	Sellopoulo	Tomb 4, Burial I	31		HM	304	912	
137	LM IIIA1	Sellopoulo	Tomb 4, Burial I or III	24	br	HM	282	918	
138	LM IIIA1	Sellopoulo	Tomb 4, Burial I	26		HM	294	909	
139	LM IIIA1	Sellopoulo	Tomb 4, Burial I	26		HM	295	910	
140	LM IIIA1	Sellopoulo	Tomb 3	6		HM	64	897	
141	LM IIIA1	Sellopoulo	Tomb 3	10B		HM	119	898	
142	LM IIIA1	Chania	tomb south of the law-courts	6	*br	CM M116	44	862	
143	LM IIIA1	Chania	tomb south of the law-courts	6	*br	CM M117	45	863	
144	LM IIIA1	Chania	tomb south of the law-courts	4A	*br	CM M119	30	860	
145	LM IIIA1	Chania	tomb south of the law-courts	4B	*br	CM M118	36	861	
146	LM IIIA1	Archanes	Tholos A, side chamber	21		HM	237	840	
147	LM IIIA1	Archanes	Tholos A, side chamber	7A		HM	71	838	
148	LM IIIA1	Phaistos	Kalyvia Necropolis, unknown grave	tripod cauldron (indeterminable form)		HM	96	869	
149	LM IIIA1	Archanes	Tholos A, side chamber	15		HM	175	839	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
150	LM IIIA1	Archanes	Tholos A, side chamber	25		HM	291	841	
151	LM IIIA1	Archanes	Tholos A, side chamber	25		HM	292	842	
152	LM IIIA1	Zapher Papoura	Tomb 14	32E		HM 1084	329	885	
153	LM IIIA1	Sellopoulo	Tomb 4, Burial I	35		HM	345	914	
154	LM IIIA1	Sellopoulo	Tomb 4, Burial III	37C		HM	352	920	
155	LM IIIA1	Archanes	Tholos A, side chamber	37D		HM	353	843	
156	LM IIIA1	Zapher Papoura	Tomb 14	43		HM	368	886	
157	LM IIIA1	Archanes	Tholos A, side chamber	45A1		HM	371	844	
158	LM IIIA1	Sellopoulo	Tomb 4, Burial I	45A2		HM	390	915	
159	LM IIIA1	Archanes	Tholos A, side chamber	45B1		HM	395	845	
160	LM IIIA1	Sellopoulo	Tomb 3	45B1		HM	397	899	
161	LM IIIA1	Zapher Papoura	Tomb 14	45B1		HM	398	887	
162	LM IIIA1	Chania	tomb south of the law-courts	45B2		CM M115	403	864	
163	LM IIIA1	Phaistos	Tombe dei Nobili, Tomb 8	45B2		HM	404	874	
164	LM IIIA1	Sellopoulo	Tomb 4, Burial I	45B2		HM	405	916	
165	LM IIIA1	Zapher Papoura	Shaft Grave 36	45B2		HM 1087	406	894	
166	LM IIIA1	Chania	tomb south of the law-courts	50		CM M114	430	865	
167	LM IIIA1	Sellopoulo	Tomb 3	50		HM	431	900	
168	LM IIIA1	Zapher Papoura	Tomb 14	50		HM 1085	433	888	
169	LM IIIA1	Zapher Papoura	Tomb 14	51		HM 1528	438	889	
170	LM IIIA1	Zapher Papoura	Tomb 14	57C1		HM 1094	449	890	
171	LM IIIA1	Sellopoulo	Tomb 3	58B1		HM	454	901	
172	LM IIIA1	Sellopoulo	Tomb 3	58B1		HM	455	902	
173	LM IIIA1	Sellopoulo	Tomb 4, Burial III	58B1	br	HM	456	921	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
174	LM IIIA1	Archanes	Phourni, Tholos A, side chamber	58B2		HM	461	846	
175	LM IIIA1	Sellopoulo	Tomb 4	58B2	br	HM	463	917	
176	LM IIIA1	Zapher Papoura	Tomb 14	58B2		HM 1093	464	891	
177	LM IIIA1	Zapher Papoura	Tomb 36a	21		HM	242	893	
178	LM IIIA1	Zapher Papoura	Tomb 36c	15		HM 1092	179	892	
179	LM IIIA1	Phaistos	Kalyvia Necropolis, Tomb 4	21		HM	240	871	
180	LM IIIA1	Zapher Papoura	Tomb 99g	4 Varia	br	AshM AE 494	38	895	
181	LM IIIA1	Chania	tomb near the law courts	21		CM M12	238	866	
182	LM IIIA1	Zapher Papoura	Tomb 14c	12		HM	164	880	
183	LM IIIA1	Phaistos	Kalyvia Necropolis, grave unknown	4A		HM	31	868	
184	LM IIIA1	Zapher Papoura	Tomb 99h	28		HM	298	896	
185	LM IIIA1	Archanes	Tholos A, side chamber	4B		HM	35	837	
186	LM IIIA1	Sellopoulo	Tomb 4	47A	Ag	HM	p. 279, no. c		
187	LM I-IIIAT			*33	*br	CM M64			MMVV no. 302
188	LM II-III A1	Ayios Ioannis	chamber tomb	33	Au	HM 758	p. 219, no. b		AGSIV no. 19
189	LM II-III A	Knossos	tomb near Knossos	one-handled goblet	Ag	HM 692			AGSIV no. 21
190	LM II-III A	Isopata	Royal tomb	*43	Ag	HM			AGSIV no. 22
191	LM IIIA2	Isopata	Tomb 4e	32A		HM 1757	308	929	
192	LM IIIA2	Archanes	Shaft Grave 4	*4A		HM	29	847	
193	LM IIIA2	Archanes	Shaft Grave 4	15		HM	176	848	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
194	LM IIIA2	Archanes	Phourni, room north of Tholos B	58B2		HM	462	859	
195	LM IIIA2	Moni		?bowl				1390	
196	LM IIIA2	Pharmakokephalo		?bowl				1452	
197	LM IIIA2	Archanes	Shaft Grave 6			HM		856	
198	LM IIIA2	Archanes	Shaft Grave 6			HM		854	
199	LM IIIA2	Archanes	Shaft Grave 2			HM		852	
200	LM IIIA2	Archanes	Shaft Grave 6			HM		858	
201	LM IIIA2	Archanes	Shaft Grave 5			HM		853	
202	LM IIIA2	Archanes	Shaft Grave 4	?cup		HM		850	
203	LM IIIA2	Archanes	Shaft Grave 6			HM		857	
204	LM IIIA2	Archanes	Shaft Grave 6			HM		855	
205	LM IIIA2	Archanes	Shaft Grave 2			HM		851	
206	LM IIIA2	Archanes	Shaft Grave 6	?lekane		HM		849	
207	LM IIIA-B ^f			*45A1	*br	CM M60			MMVV no. 304
208	LM IIIB	Gournes	Tomb 2	40		HM 2019	363	925	
209	LM IIIB	Gournes	Tomb 2	57C2		HM 2022	450	926	
210	LM IIIB	Kalami		?vase				1476	
211	LM IIIB	Tefeli		?lekane				1427	
212	LM IIIB ^f			*40	*br	CM M62			MMVV no. 308
213	LM IIIB ^f			*57C2	*br	CM M63			MMVV no. 307
214	LM IIIC	Moulana	Tholos A	29		HM 1004	300	1838	
215	Postpalatial	Mochlos	Tomb 10	*47A				1762	
216	Postpalatial	Chania	grave	43		CM M157	367	867	

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
217	Postpalatial	Episkopi	Kalyvotopos, Tomb A	45B1		HM 2859	396	931	
218	Postpalatial	Starnioi	Palatona, Tomb Γ	50		HM (exhibition).	432	933	
219	Postpalatial	Sitia region		57B		ANM	448	938	
220	MM III - LMIII B ^c	Gortyna	Country House Room 9	74A		HM	34		
221	Unspecified LM	Phaistos	outside the palace	6	Cu	HM	63	876	
222	Unspecified LM	Malia vicinity	Azmo	6		HM 2085	60	797	
223	Unspecified LM	Malia vicinity	Azmo	6		HM 2086	59	796	
224	Unspecified LM	Phaistos	?palace	6		HM	62	875	
225	Unspecified LM	Zakros	grave, House C	tripod cauldron (indeterminable form)		HM	95	821	
226	Unspecified LM	Knossos	house in the vicinity of the palace	32D		HM 1082	322	783	
227	Unspecified LM	Phaistos	palace	49C		HM	427	877	
228		Ayia Triada	store room	21		Mus Pig 75214	239	1783	
229		Ayia Triada		1C		HM	15	1784	
230		Ayia Triada		1C		HM	16	1785	
231		Ayia Triada	store room	hydria (unknown type)		HM	251		
232		Knossos		38BIV		AshM AE 839	p. 249		
233		Moulana	Tholos A	45 (?)		HM 1002	412		
234		Moulana	Tholos A	45 (?)		HM 1002	412A		
235		Heraklion	east of the museum	33	Ag	HM 405	p. 219, no. c		AGSW no. 18
236		Crete		*38B	Cu	London, private collection			AGSW no. 24

No.	Period	Site	Context	Type	Metal	Collection	BKMK	BLMC	Other Ref.
237		Palaikastro		*32A	*br	BSA PK 03/8053			

Metal Vessel Analyses

The tables here are the expanded versions of **Table 2** and **Table 3** in Chapter One, showing full details and references for analyses which have been supplied in various publications. **Table 6** lists compositions of vessel bodies and **Table 7** lists those of vessel attachments. The data categories are described below.

Description

The descriptions are those supplied by the publications from which the analyses come. These are listed in the Reference column (see below).

Type

Where possible, the type number from Matthäus's *BKMK* is supplied.

Collection

Where it is known, the museum and its collection number are given. The abbreviations are 'HM' for the Heraklion Archaeological Museum and 'AshM' for the Ashmolean Museum.

Site and Period

Sites and periods are those provided by the authors of the analyses or from the catalogue of Minoan metal vessels in Appendix One. Abbreviations of sites listed here are Malia QM for Malia Quartier Mu and UM for the Minoan Unexplored Mansion at Knossos.

Cu, Sn, As, Pb

These columns list the amounts of copper, tin, arsenic and lead published in the analyses.

Reference

The titles of the sources of the analyses are abbreviated. Numbers from *BLMC* are those from *BLMC* Appendix V.2. Abbreviated titles which have not been commonly used previously in this study are as follows:

CBAC	H. Mangou and P. V. Ioannou. "On the Chemical Composition of Prehistoric Greek Copper-Based Artefacts from Crete."
CBAUM	H. W. Catling and R. E. Jones. "Analyses of Copper and Bronze Artefacts from the Unexplored Mansion, Knossos."
MFGS	Jeffrey S. Soles and Zofia Anna Stos-Gale. "The Metal Finds and their Geological Sources."
OMQM	Christiane Éluère, "Appendice III. Étude en laboratoire de quelques objets métalliques du Quartier Mu."
ST4	H. W. Catling and R. E. Jones. "Sellopoulo Tomb 4: Some Analyses."

BLMC A V.I

The numbers supplied here are the reference numbers to metal analyses listed in Hakulin's *BLMC*, Appendix V.I.

Cat.

The numbers listed here are catalogue numbers from the catalogue of Minoan metal vessels in Appendix One.

Table 6. Alloy Compositions of Vessel Bodies

#	Description	Type	Collection	Site	Period	Cu	Sn	As	Pb	Reference	BLMC A V.I	Cat.
1	tripod cauldron body	6	HM	Phaistos	LM	98.212	0	traces	traces	BKMK 104	72	221
2	two-handled basin	10B	HM 2195	Malia	MM IIIB	100	0			BLMC no. 786	104	14
3	two-handled basin	10A	HM 1581	Mochlos	LM IB	100	0			BLMC no. 799	103	45
4	large cauldron	1A	HM	Tylissos	LM IB	100	0			BLMC no. 810	102	42
5	tripod cauldron body	5	HM 3068	Malia QM	MM II		0.16	2.2	0.69	OMQM Table 7, no. 37		7
6	tripod cauldron body	5	HM 3069	Malia QM	MM II		0.17	1.9	0.68	OMQM Table 7, no. 38		6
7	vase base			Malia QM	MM II		0.543	1.7	0.981	OMQM Table 7, no. 24		
8	vase			Malia QM	MM II		0.83	1.14	1.14	OMQM Table 7, no. 9		
9	hydria body		HM 703b	Ayia Triada	LBA	82.73	0.19	0.44	0.08	CBAC Table 3	30	
10	pot body		HM 833b	Ayia Triada	LBA	90.75	0.2	0.8	0.04	CBAC Table 3	34	
11	pitcher body		HM 1089b	Knossos	LBA	66.78	0.21	0.21	0.09	CBAC Table 3	6	
12	laver body		HM 1254b	Ayia Triada	LBA	90.44	0.39	0.1	0.04	CBAC Table 3	43	
13	laver body		HM 2073b	Knossos	LBA	82.67	0.91	0.33	0	CBAC Table 3	17	
14	rim			UM	LM II		1	1		CBAUM 63		
15	rim			UM	LM II		1			CBAUM 63		
16	hydria body	21	HM 1088b	Zapher Papoura	LM IIIA1	81.6	2.37	0.24	0.07	CBAC Table 3	4	122
17	rim			UM	LM II		4			CBAUM 63		
18	hydria handle	21	HM 1088a	Zapher Papoura	LM IIIA1	64.68	4.31	0.03	0.09	CBAC Table 3	3	122
19	body			UM	LM II		5			CBAUM 63		
20	body			UM	LM II		5.5			CBAUM 63		
21	body			UM	LM II		5.5			CBAUM 63		
22	bowl			Mochlos	LM IB	93.4	6.4	0.3	<0.2	MFGS Table 1, CA 19		76
23	laver body	44	HM 2075	Knossos	LM IA	87.16	6.72	0.13		CBAC Table 3	101	38

#	Description	Type	Collection	Site	Period	Cu	Sn	As	Pb	Reference	BLMC A V.I	Cat.
24	laver body		HM 2069	Knossos	LBA	69.46	6.78	0.08	0	CBAC Table 3	15	
25	scale pan		HM	Sellopoulo	LM IIIA1		8.5			ST4 no. 9		
26	bowl	*44		Mochlos	LM IB	90.9	8.6	<0.2	<0.2	MFGS Table 1, CA 18		72
27	laver body	45B2	HM 1087a	Knossos	LM IIIA1	82.72	8.76	0.23	0.04	CBAC Table 3	1	165
28	deco sheet			UM	LM II		9			CBAUM 63		
29	pan	4	AshM AE 494	Zapher Papoura	LM IIIA1		9.1		1.1	BLMC no. 895	153	180
30	lamp w/ skillet handle	58B1	HM	Sellopoulo	LM IIIA1		9.4			ST4 no. 7	211	173
31	body			UM	LM II		9.5			CBAUM 63		
32	body			UM	LM II		9.5			CBAUM 63		
33	pan	15	HM 1092	Zapher Papoura	LM IIIA1	82.93	10.34	0.31	0.04	CBAC Table 3	7	178
34	deco sheet			UM	LM II		10.5			CBAUM 63		
35	rim			UM	LM II		11			CBAUM 63		
36	body			UM	LM II		12			CBAUM 63		
37	rim			UM	LM II		12.5	1	1	CBAUM 63		
38	oinochoc body	24	HM	Sellopoulo	LM IIIA1		15			ST4 no. 1	210	137
39	body			UM	LM II		15-17.5			CBAUM 63		
40	lamp w/ skillet handle	58B2	HM	Sellopoulo	LM IIIA1		>20	1	1	ST4 no. 3	209	175

Table 7. Alloy Compositions of Miscellaneous Vessel Attachments

#	Description	Type	Collection	Site	Period	Cu	Sn	As	Pb	Reference	BLMC A V.I	Cat.
41	laver handle		HM 1254a	Ayia Triada	LBA	88.89	0.19	0.74	0.16	CBAC Table 3	42	
42	hydria handle		HM 703a	Ayia Triada	LBA	89.64	0.2	0.4	0.28	CBAC Table 3	29	
43	handle		HM 1544a	Ayia Triada	LBA	91.93	0.2	0.87	1.08	CBAC Table 3	47	
44	handle		HM 1544	Ayia Triada	LBA	89.14	0.2	1	3.52	CBAC Table 3	46	
45	pitcher handle		HM 1089a	Knossos	LBA	84.35	0.22	0.31	1.68	CBAC Table 3	5	
46	handle			Malia QM	MM II		0.44	0.57	0.2	OMQM Table 7, no. 40		
47	laver handle		HM 2073a	Knossos	LBA	87.17	0.63	0.24	0.09	CBAC Table 3	16	
48	pot handle		HM 833a	Ayia Triada	LBA	91.49	0.79	0.72	0.9	CBAC Table 3	33	
49	handle			UM	LM II		1			CBAUM 63		
50	handle			Malia QM	MM II		1.3	1.7	0.9	OMQM Table 7, no. 39		
51	tripod cauldron leg	6	HM	Sellopoulo	LM IIIA1		5.8			ST4 no. 5	207	128
52	handle			UM	LM II		6			CBAUM 63		
53	handle			Malia QM	MM II		8.9	0.68	0.213	OMQM Table 7 no. 8		
54	laver handle	45B2	HM 1087b	Knossos	LM IIIA1	81.1	9.7	0.11	0	CBAC Table 3	2	165
55	handle			UM	LM II		12.5			CBAUM 63		
56	oinochoe handle		HM	Sellopoulo	LM IIIA1		16			ST4 no. 1		137
57	handle			UM	LM II		20-22.5			CBAUM 63		
58	hydria protome		HM	Sellopoulo	LM IIIA1		5.5			ST4 no. 4		135
59	oinochoe masking band		HM	Sellopoulo	LM IIIA1		20			ST4 no. 1		137

Films of the Reconstructed Minoan Vessel Manufacturing Processes

Please see the enclosed disc.⁵⁸⁰ Video files are in M4V format and are viewable with Apple QuickTime Player, iTunes, VLC Media Player, RealPlayer and the version of Windows Media Player included with Windows 7.

Part One: Annealing

Part Two: Sinking

Part Three: Raising

Part Four: Forging Material Thinner

Part Five: Finishing

Part Six: Cutting

Part Seven: Hole-Punching

Part Eight: Riveting

⁵⁸⁰ Filming and film production by Lan Nguyen-hoan.

Ag 925. sterling silver

alloy. A metal which is composed of two or more elements. Examples include tin bronze, composed of copper and tin, and sterling silver, composed of silver and, traditionally, copper.

annealing. Softening metal which has become work-hardened by heating it to a temperature and for an amount of time which causes the grains of the metal to recrystallise into a more malleable structure. Quenching the metal at this temperature can preserve the new structure.

arsenic bronze. See bronze.

bench pin. A small piece of timber which projects from the front of a jeweller's bench and which an item being worked on is held on or pushed against.

bivalve mould. Also called a closed or two-piece mould. Made from two halves, often with the matrix carved into both halves. The matrix for the item to be cast has a funnel connecting it to the outside of the mould into which molten metal is poured. See also open mould, lost-wax casting.

brass. An alloy of copper and zinc.

brazing. A technique for joining metal which uses molten brass as the binding material. The term is sometimes used to refer to soldering.

bronze. In antiquity, an alloy composed primarily of copper and tin. The term is sometimes used to refer to an alloy of copper and arsenic. In this study, where the two types of bronze are distinguished from one another, they are referred to as tin bronze or arsenic bronze.

burnishing. A method for polishing metal by rubbing the surface with a hard, polished material such as steel or haematite.

butt joint. A term used to refer to a joint on a metal object (and other materials, especially wood) where the join of two components is formed by butting the pieces together as opposed to overlapping them.

butt chisel. A chisel with a straight cutting edge.

caulking. Thickening the rim of a vessel by forging its edge into the wall.

chasing. A method for creating intaglio designs in metal, usually sheet, using a blunt punch to work the design from the front. The punch is struck with a hammer while the point is moved over the surface of the metal, which sits on a moderately malleable substance such as bitumen or wax. Often used in combination with repoussé.

colloid hard-soldering. A method for joining gold or silver components. The surfaces of the components are coated with a paste of a copper compound and an organic glue and heat is applied. The carbon in the glue helps to reduce the copper compound to metallic copper, forming an alloy on the metal surfaces which has a lower melting temperature than the surrounding metal. As a result, the metal components are joined together. The technique was commonly used in antiquity in the production of gold jewellery and is best known for its use in granulation. Also known as colloidal soldering, reaction soldering, diffusion soldering and diffusion bonding. See also soldering, cf. hard soldering, soft soldering, brazing.

crimping. (In this study) a hammering method used to transform a flat metal disc into a shallow dish with a flat base and straight sides. An outer perimeter of the disc is hammered into flutes which radiate out from the centre. These flutes are subsequently hammered flat. As a result, the outer, crimped perimeter is raised upwards from the base.

cross-peen hammer. A hammer with a rounded wedge-shaped working face.

crucible. A bowl in which metal is melted, usually made from a refractory clay.

finishing. The processes used to remove scratches from a metal surface and ultimately create a polish. Typically, finishing requires the use of successively finer grades of abrasive, which result in progressively finer cuts on the surface. On an unfinished or unpolished surface, scratches in the surface cause light rays to be

scattered, creating a dull surface. As the surface becomes closer to being perfectly smooth, light rays reflect in parallel lines, creating a reflective surface.

flux. In casting and smelting, a deoxidising substance added to molten metal to lower the melting point and help to maintain a reducing atmosphere. In soldering, a substance applied to metal before heating to prevent oxides from coating the metal before the solder has fused with the surfaces. Borax is a typical modern flux which was also used in antiquity.

forging. Shaping metal by hammering it onto a surface, typically an anvil. The metal is sandwiched between the hammer and the surface of the anvil.

gilding metal. A specific type of brass containing approximately 95% copper and 5% zinc.

hard solder. A solder with a melting temperature above 550°C. Usually refers to silver-copper alloys used as solder, but also applies to gold-silver and gold-copper solders. See also soldering, cf. colloid hard-soldering, soft soldering, brazing.

hardness Vickers. A scale used to determine the hardness of a material, determined by its resistance to plastic deformation for a given amount of applied force. Other hardness scales include the Rockwell Hardness Scale and the Brinell Hardness Scale.

hoard. An archaeological deposit of valuables which has usually been deposited to hide precious items and was never retrieved by the owner.

inlay. A method for setting one type of metal into the surface of another for decorative effect. The surface of the backing metal is worked with tools to create channels or larger open recesses, the inlay metal is set into the channels and recesses and may be fixed in place either with an adhesive or by working the walls of the channels and recesses with tools to hold the inlay in place.

lost-wax casting. Also called *cire perdue* or investment casting. A method for casting metal. The method referred to in this study is known as direct casting. A model of the object to be cast is first made in wax and subsequently coated with an investment material such as clay or plaster. This is then heated to melt out the

wax, which empties through a channel incorporated into the design. The result is a hollow mould into which molten metal can be poured to fill the void left by the wax model. The metal object is removed by breaking the mould. See also bivalve mould, open mould.

matrix. The void in a mould which is the negative of an item to be cast.

mould. See bivalve mould, lost-wax casting, open mould.

open mould. Also called a one-piece mould. A mould with a matrix which is open.

Molten metal is poured directly into the matrix. An open mould has no funnel connected to the matrix, and the molten metal is poured directly into the matrix. See also bivalve mould, lost-wax casting.

ore. Rock from which a metal is smelted. Copper ores include malachite, azurite and chalcopyrite. Galena is an ore of silver and lead and cassiterite an ore of tin. See also smelting.

pickling. The use of dilute acid (a 'pickle') to remove oxides from the surface of metal which has become oxidized by heating. A common pickle used today is dilute sulphuric acid.

piercing saw. A small hand-held saw with a very fine blade used by jewellers and metalsmiths to cut metal.

piriform. Literally, pear-shaped. In the context of vessel forms, a vase with a narrow base expanding to a broad shoulder and which narrows again towards the opening. Similar to an upside-down pear.

planishing. A hammering method whereby sheet metal is forged with a flat-faced or slightly-domed hammer face on a smooth, usually steel, stake or anvil surface. As a result, the sheet is smoothed and becomes thinner, thereby stretching. Planished sheet usually has a distinctive faceted surface.

pot bellows. A type of bellows used to introduce a draft into a metallurgical hearth or furnace. It consists of an open clay pot with a nozzle in its wall connected to a pipe which feeds into the burning fuel. A piece of leather with a slit in it covers

the top of the pot. When this is pumped up and down, air drawn through the slit is forced into the fuel via a tuyère.

quenching. Plunging hot metal into a liquid such as water or oil, causing it to cool more quickly than if left to air-cool. Quenching typically freezes the crystals of the metal in the structure which they take at the pre-quenching temperature. See also annealing.

raising. Creating a hollow, thin-walled metal form by hammering metal sheet over a former called a stake.

reducing atmosphere. A condition, usually within a furnace or a hearth, where oxygen is removed to prevent oxidization of other gases and molten materials. See also flux, smelting.

refractory. The property of a substance which allows it to remain stable at high temperatures. Refractory ceramics were used in antiquity to make crucibles, tuyères and furnaces.

repoussé. A method for creating relief designs in sheet metal using a blunt punch to work the design from the back. The punch is struck with a hammer while the point is moved over the surface of the metal, which sits on a moderately malleable substance such as bitumen or wax. Repoussé is usually used in combination with chasing.

riser. A channel in a lost-wax mould which allows air to escape from the matrix as molten metal is poured into the mould. See also lost-wax casting.

running-on. A hot-joining method for joining metal components by pouring molten metal over the joint. Also called burning.

sinking. Creating a hollow, thin-walled metal form by hammering metal sheet or plate over and/or into a hemispherical void. Sometimes called blocking or hollowing.

skin bellows. A type of bellows made from the skin of an animal.

slag. A liquid waste product formed during most metallurgical processes which involve metal in its molten stages. It is always created during smelting and refining, but

sometimes also during casting, if the metal is impure, and during hot-forging of iron. Liquid slag hardens into a brittle, vitreous substance as it cools.

smelting. A chemical process used to extract metal from an ore. In its simplest form, extraction requires high temperatures and a reducing atmosphere, both of which are achievable in a reducing furnace. The high temperature and reducing atmosphere contribute to transforming the components of the ore into the liquid metal and liquid waste products, or slag.

soft solder. Traditionally, a solder composed of tin and lead, which has a melting temperature between 185 and 300 °C. The lead component of most modern soft solders is often replaced with a less toxic metal. See also soldering, cf. brazing, hard-colloid soldering, hard solder.

soldering. The use of an alloy to join metal components. The melting temperature of the solder is lower than that of the main components, so that applied heat will only melt the solder, which binds with the surfaces of the other metal components, joining them together. See also flux, soft solder, hard solder, hard-colloid soldering, brazing.

stake. A wooden or metal form over which sheet metal is hammered to create a hollow form such as a vessel.

sterling silver. Traditionally, an alloy of silver consisting of 92.5% silver and 7.5% copper. Alternative elements such as germanium may be used instead of copper to reduce the oxidization problems which commonly occur with the use of sterling silver.

tin bronze. See bronze.

tuyère. A pipe through which air is forced into a furnace or hearth for smelting or melting metals. In antiquity, tuyères were made from refractory ceramics.

work-hardening. The hardening of a metal which occurs with plastic deformation, generally by hammering.

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